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LOW EMISSIONS COMBUSTION SYSTEM RETROFITS FOR MATURE FRAME GAS TURBINE POWER PLANTS

Ian Summerside[†], Nicolas Demougeot, Jeffrey A. Benoit

Power Systems Mfg, LLC (PSM)
An Alstom Company
1440 West Indiantown Road
Jupiter, Florida, USA
([†]ian.summerside@psm.com)

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Abstract

Current and future emissions regulations show a trend requiring significant reductions in emissions on Industrial Gas Turbines (IGT). Similar regulations have already been put in place by the Environmental Protection Agency (EPA) in the US and other global regions are following suit.

This paper discusses the various options available for a cost conscious mature frame IGT operator to fulfill these requirements. Primarily focusing on the product development required to configure and implement an ultra low emission system onto a Frame 7B gas turbine. The novel approach allowed the upgrade to perform at low emissions levels, without any modifications to the turbine section or increase in firing temperature.

Experimental methods are discussed and results from the first conversion are also shown. The GT stack emissions were reduced from ~40ppm NOx to <5ppm NOx and CO reductions in a similar range. Close to 7 million litres of water has also been saved annually, through the removal of the diluent water injection system.

1. Introduction

Continuing pressure by from both Province and nation-wide Air Quality Management Systems (AQMS), the latest Base-Level Industrial Emissions Requirements (BLIERs) require a significant reduction in emissions on both new Industrial Gas Turbine (IGT) installation and also the existing installed base of IGT's in Canada. Similar regulations have already be put in place by the Environmental Protection Agency (EPA) in the US and other global regions are following suit.

In the United States the EPA's most recent Clean Power Regulation focus is to reduce ozone-causing gas turbine emission levels requiring power plant operators to aggressively evaluate cost & performance strategies to ensure profitable operation.

Options typically include shutting down or selling facilities, procuring emission credits in the marketplace, changing turbine operational profile, replacement of combustion systems with more modern technology and/or installation of Selective Catalytic Reduction (SCR) systems. Selection among these options are driven by complex plant and company-wide risk-based cost benefit analyses to select the best solutions.

The mature turbine life extension assessments must consider projected plant utilization, turbine operational experience, regulatory dynamics, and cost and implementation aspects to properly evaluate future profitability. Life extension substantiation can be further complicated by changes in environmental and economic conditions coupled with governmental and corporate strategies all shifting with time.

One particular power producing peak power to the Federal Energy Regulatory Commission (FERC) regional power market in the north east United States (the PJM Regional Transmission Organization) faced such a challenge in 2013. The local state High Energy Demand Day (HEDD) regulatory mandate stated that the plant shall reduce its NOx emission to less than 10 ppm and CO emission to less than 80 ppm between 80% and 100% load for ambient temperatures above -11°C, those requirements being relaxed to 12 ppm and 100 ppm respectively below -11°C, and between 90% and 100% load. The new regulations were to come into force in 2015.

This plant consists of 4 x 1 Frame 7B units, configured to run in combined cycle or simple cycle with an exhaust bypass stack. These units, originally commissioned in 1974 operate at approximately 49 MW for each unit in simple cycle mode. They were configured with diffusion flame combustions systems with water injection as a dilutent to control NOx creation. For mature turbines already using steam and/or water injection for NOx abatement, the choices in meeting more stringent emissions regulations are currently limited to converting the combustion system to a lean premix design, improving/adding SCR capability or replacing the turbines with more modern equipment. The financial analysis and details of these various considerations and tradeoffs are considered company proprietary.

Because of design limitations of the existing gas turbine exhaust system equipment at the plant, coupled with packaging constraints making the SCR installation impractical, it was concluded that a retrofit of the gas turbine combustion systems would be the best option based on life cycle cost, installation schedule and overall implementation complexity. Therefore, the operator decided to convert the 7B gas turbines from high-NOx emitting diffusion combustion systems to an ultra-low NOx combustion system technology.

Additional plant modifications furnished included new fuel delivery systems, control systems retrofit for both the Gas Turbines and the Balance of Plant and Combustion Dynamics Monitoring Systems (CDMS).

Prior to the combustion conversion retrofit a test was conducted to gather emissions and operational data showed NOx emission levels at about 35 ppm with water injection across most of the operating range. While CO was varying between 20 and 100 ppm depending on load. The dry values (no water injection) being around 90 ppm and 1 ppm for NOx and CO respectively. Note that diluent water injection of upwards to 140 liters per minute was used to control emissions in the original combustion system.

The LECIII® combustion systems would divide the permitted NOx emission by at least a factor of 7 and reduce CO to sub 25 ppm levels. It would also save around 6.8 million liters of water for the whole power plant, based on a 200 hr average annual run time for each of the units.

2. Low Emissions Combustion Technology

The LECIII® technology was first incorporated into GE Frame 7E gas turbines in 1998. This can-annular, reverse-flow combustion system, shown in Figure 1, was designed to be a direct replacement into an existing gas turbine outfitted with the OEM DLN1 system. To date, the PSM fleet of these low emission combustion systems has surpassed 1.5 million hours operation and over 18,000 starts. The system is installed in 70 units including an industrial co-generation facility in Alberta, Canada, completed in 2001.

This combustion technology has over 25 patented features that will allow end users to achieve as low as sub-4 ppm NOx emissions over a premix operating range with low CO, combustion dynamics and turndown from base load operation.

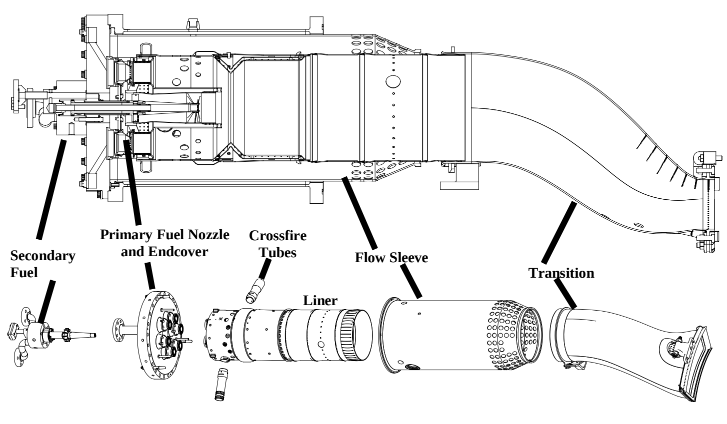


Figure 1. PSM's LECIII® Combustion System Cross Section

Exhaust Emissions Considerations

In natural gas fired industrial gas turbines, today's targeted and regulated emission pollutants are clearly NOx and CO. While the power industry is beginning to seriously address the environmental consequences and capture of power plant CO_2

emissions, it is a topic outside the bounds of this paper. NOx formation in natural gas-fired combustion turbines is a function of temperature and residence time. The process, as discussed by Turns [1], is known as thermal NO_x production, in which high temperatures cause a decomposition of atmospheric nitrogen (N_2) into single atoms that then react with oxygen to form nitrogen oxide species. The decomposition of N_2 is minor below about 1565^{o}C, and corresponding NOx formation is also small. But NOx production increases rapidly as the temperature increases beyond this point. Average lean premix combustion system temperatures in a turbine are typically lower than this 1565^{o}C threshold temperature, but certain local regions within this chemical reaction zone may be significantly hotter, and it is in these locations that excess NOx will rapidly form. Minimizing these rich local areas by enhanced mixing is a key to reducing NOx.

Carbon monoxide is generated by incomplete combustion. In an ideal combustor, CO formation is a short-lived, intermediate by-product that is allowed to fully oxidize to CO_2 at the completion of combustion. However, operational combustion systems in gas turbines are not ideal due to cost considerations, design philosophy and system material cooling techniques. Because of this, incomplete combustion and resultant CO formation is a reality. As with NOx, enhanced mixing will improve combustion efficiency and reduce CO emission levels. Therefore, any unmixed 'cold' stream within the reaction area needs to be eliminated to assure CO does not become a problem.

Technology Overview

The key mixing features of this low emission combustion technology include a reverse-flow cooled venturi, increased dilution air to the head-end premixer enabled by the enhanced cooling efficiency of effusion cooling, and a fully-premixed "Fin Mixer" secondary fuel nozzle. These features can be seen in figure 2, will be discussed individually, and all contribute to the operational results of the combined system.

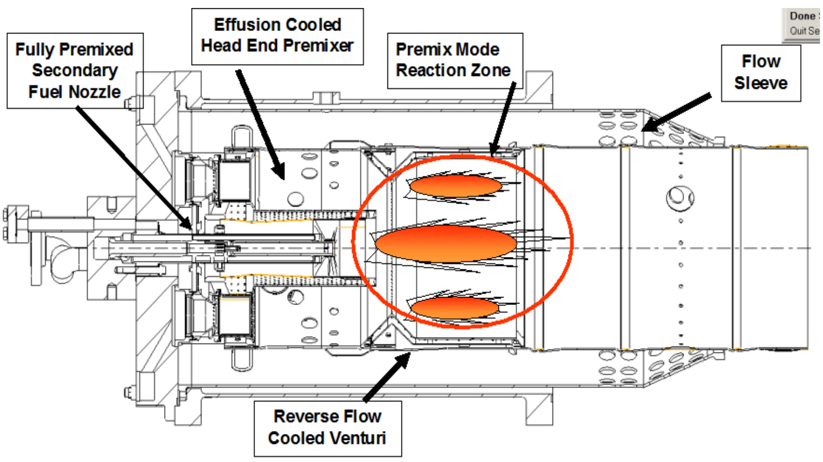


Figure 2. Combustion System Description

Reverse Flow Cooled Venturi

The venturi shown in Figure 4 plays a key role in the combustion process. The forward cone of the venturi is immediately downstream of the 'head-end' premixer, and it forces convergence and acceleration of the premixing gas and air mixture. At the venturi 'throat', premixed mixtures are discharged into the reaction zone at very high velocities. Immediately downstream of the throat is the venturi's divergent cone, which creates a sudden expansion and strong recirculation region. This strong recirculation is essential for combustion stability. The high velocities of the premixed flow at the throat serve to prevent flash back during the premix combustion mode. Throat velocities are sufficiently high in the bulk mainstream to be well in excess of reacting flame speed, even when coupled with the dynamic oscillations created from combustion noise.

In all operating modes, one or both of the venturi cones are exposed to high temperatures. The standard technique for keeping the venturi from overheating is convective cooling, in which the venturi supply air is channeled through an annular space between an inner and an outer wall.

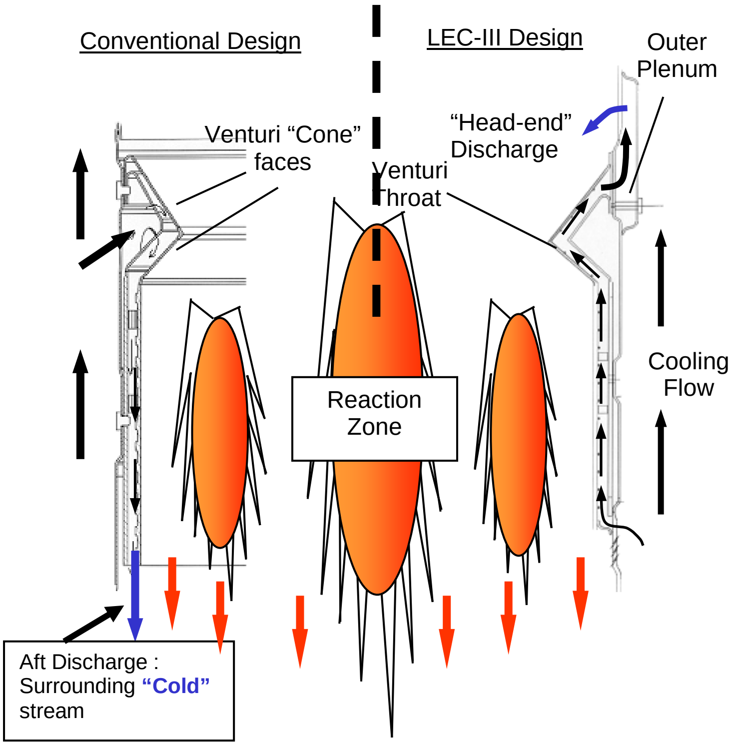


Figure 3. Venturi Cooling

Figure 3 illustrates the two different venturi design approaches. In conventional designs, the air enters the venturi cooling channel at its forward end near the throat, and the air flows aft, in the same direction as the combustion gas, discharging into the combustor hot flow stream on near the aft end of the reaction zone. The cooling is effective in maintaining stable venturi metal temperatures; however a large 'cold' stream of air is generated, surrounding the reacting gas volume. The stream represents a significant percentage of the entire liner flow, so it is a significant flow feature within the reaction zone. This cold air interacting with the hot gas exiting the venturi also stops or “freezes” CO from fully oxidizing to CO_2 and limits the combustor’s operational range. In the ultra low emission combustion system, the cooling air enters the venturi at its aft end location and flows forward, opposite of the hot gas flow, to cool its cylindrical section and throat area. The air picks up heat by similar convective heat transfer, with the augmentation assist of ‘trip strips’, a commonly used feature in turbine airfoil cooling. At the extreme forward end of the venturi, the cooling air is collected in an outside plenum. This annular plenum then discharges the preheated cooling air into the ‘head-end’ chamber for use in premixing. This air has now been ‘preheated’, which increases its discharge jet velocities to enhance mixing immediately at the point of head-end flow convergence. As result, the venturi cooling air is fully mixed, so that the conventional ‘cold’ stream is completely eliminated.

Increased Premixer Dilution Air

Conventionally, the head end premixer dome plate has impingement cooling. The liner walls are louver cooled, which creates a film of cooling air on the wall surface. In the ‘head-end’ of the ultra low emission combustion system liner as shown in Figure 4, the outer wall and dome plate is cooled by use of shallow-angled effusion cooling holes.

Effusion cooling allows substantially less air required for wall cooling, and therefore the requirement for typical industry standard thermal barrier coating can be eliminated as discussed by Lefebvre [2]. By design, the additional cooling air is now put into the ‘Head end’ dilution jets to create enhanced mixing. These effusion holes are precisely controlled and the airflow requirements are stringent, to assure that liner-to-liner airflows within the system are held very consistent. This airflow control in combination with close fuel flow control maximizes lean blow-out margin, minimizes exhaust temperature spreads, eliminates any ‘hot spot’ to improve component durability and also reduces NOx emissions.

Figure 4. LECIII® Combustion Liner Head End Mixer Effusion Cooling Holes

Fully Premixed "Fin Mixer" Secondary Fuel Nozzle (SFN)

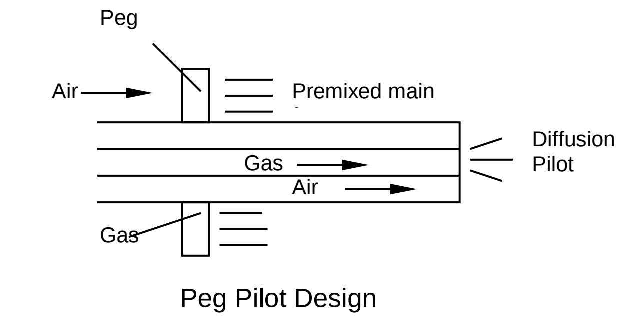
The secondary fuel nozzle is a key contributor to the demonstrated stability of the 7E/EA OEM DLN1 combustion system. The secondary fuel nozzle sets up a central 'pilot' zone of reaction and recirculation that acts as the continual ignition source for the surrounding reaction zones.

By design, this secondary reaction zone is a richer mixture, burning hotter to provide excellent combustion stability. In the conventional DLN1 system of the 7EA, this secondary fuel flow is actually channeled through two separate circuits. The majority of the fuel is discharged from 'pegs' near the nozzle's mid section. This fuel premixes with air as it travels along the length of the nozzle. The second circuit within the nozzle has a small amount of fuel discharging at the tip (extreme aft end), which is not premixed at all. It burns in a 'diffusion' mode of combustion. This region has some areas of reaction temperatures above 1925^{o}C and the associated NOx formation is significant. Although only a small amount of the total fuel flow, its contribution to the system's total NOx formation can be significant.

Elimination of this 'diffusion' burning aspect of the conventional nozzle has been the focus of the ultra low emission combustion system's secondary fuel nozzle design evolution. A significant amount of rig and engine development testing has been conducted in development of this nozzle design by Oumejjoud et al [4].

As result, the "Fin Mixer" SFN has demonstrated through engine verification and validation the ability to significantly reduce NOx. This improvement is simple in concept and implementation, and it provides a step change in emission reduction in an already low emission combustion system.

The discussed variations of SFN fuel distribution designs are illustrated in Figure 5 and Figure 6 provides comparative high pressure rig testing results from three (3) design configurations, the OEM baseline peg pilot fuel nozzle design ("Well Mixed"), and two variations of the fin mixer with different fuel/air mixing schemes ("Semi-perfectly Mixed, Perfectly Mixed") showing the emission trending and tradeoffs.



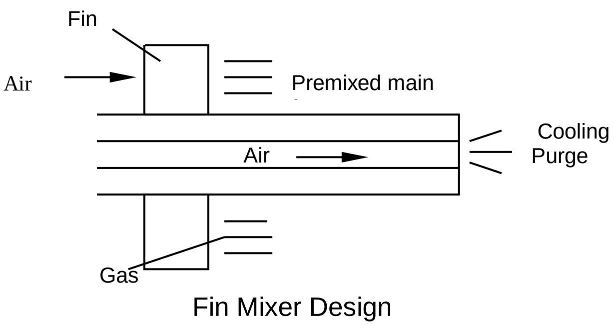
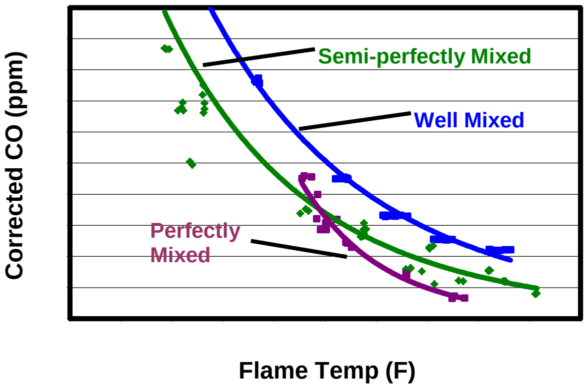


Figure 5. Secondary Fuel Nozzle Differences



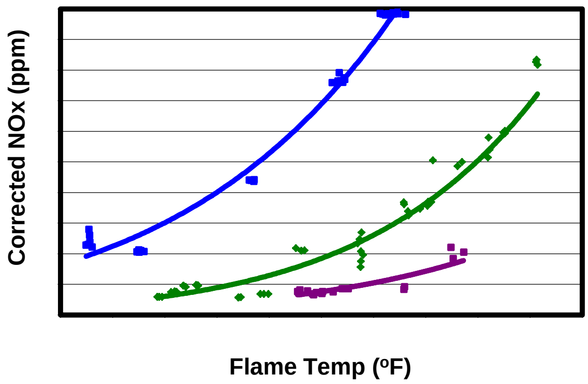


Figure 6. Fuel Nozzle Emission Results [4]

3. Key Elements of the Conversion Work Scope

Figure 7 provides a graphical overview of the on base modifications that were part of this effort.

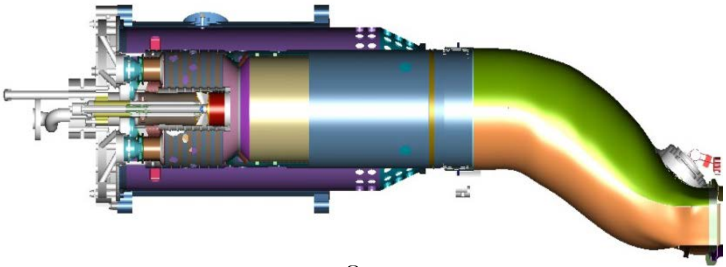


Figure 7. PSM's Frame 7/9 LECIII® Combustion System Cross Section

LECIII® System Hardware Scope of Supply:

- Combustion Liners
- End Cover / Primary Fuel Nozzle Assemblies
- Secondary Fuel Nozzles (SFN)
- Flow Sleeves
- Transition Pieces and Bullhorn Brackets
- Cross Fire Tubes, Clips and Spool Pieces
- Combustion Stub Cases
- Combustion Dynamics Monitoring System (CDMS)
- NERC compliant Monitoring & Diagnostic Server

Key Upgrade / Conversion Scope of Supply:

- New Gas Fuel Skid, including all piping and manifolds
- Combustion Ignition & Flame Detection System
- Flame Scanners (redundant primary flame zone and secondary flame zone)
- LECIII® combustion System controller
- BOP Control Room Equipment

The key technology elements of this conversion effort was current production 7EA ultra low emission combustion system fuel nozzles, flow sleeve, combustion liner and transition pieces.

Finally, the obsolete, existing OEM gas turbine control system was decommissioned and a brand new system was installed, both for Gas Turbine Control and the Balance of Plant. The old control logic was reviewed and completely re-programmed. Additions included controls logic for the ultra low emission combustion system and fuel skid, engine protection and associated auxiliaries with the ultra low emission combustion system controller (flame scanner detection system, Combustion Dynamics Monitoring System (CDMS) and IGV control).

4. Design Challenges and Solutions

While typical conversions from diffusion flame combustion systems to the ultra low emission combustion system on Frame 7B/E, 7E and 7EA are relatively straightforward as described in [4] - [8], there is added complexity and challenges when applying the technology to low firing, mature 7B gas turbine.

Prior to this project, the ultra low emission combustion technology had been successfully implemented on Frame 7B/E, 7E and 7EA with firing temperatures ranging from 1075°C to 1150°C (1965°F to 2100°F). The 7B is fired at 1000°C (1840°F) or 52°C (125°F) colder than the lowest fired ultra low emission combustion system unit.

Dilution Air Strategy

With the ultra-precise metering of the air flow entering the Reaction Zone downstream the venturi is critical to achieve both NOx and CO targets while maintaining sufficient margin to elevated combustion dynamics and Lean Blow-Out (LBO). Those targets are achieved by sizing the combustor to obtain a typical Reaction Zone Temperature (T_{RZ}) which is similar across all ultra low emission combustion system configurations, regardless of the Frame size and unit firing temperature.

Because of its relatively low firing temperature, the 7B burnt gas temperature profile inside the combustor and transition piece shows a severe drop of about 426°C (800°F) between the Reaction Zone (T_{RZ}) and the turbine inlet (TIT or firing temperature). As a consequence, the amount of dilution air injected between the Reaction Zone and the turbine inlet was, relatively speaking, significantly larger than for any other Frame 7E equipped with this ultra low emission combustion system. The dilution air is typically injected at one plane at the aft end of the liner, and one to three planes inside the transition piece.

It is well known that injecting a massive amount of cold air into the main hot gas stream can generate a lot of CO through two mechanisms, one global and one local:

1. A large amount of dilution air injected too “early” into the main hot gas stream can “quench” the overall combustion process too fast, favoring partial oxidation of C into CO instead of CO_2
2. Smaller amount of cold air that would not be large enough to “quench” the overall combustion process also generates some CO locally at the interface between the cold air jet and the main hot gas stream

As a consequence, “late” (closer to the turbine inlet) and distributed dilution is the best approach to prevent massive CO formation.

On the other hand, injecting cold air into the main hot gas stream too close to the turbine inlet will prevent sufficient mixing and dilution between the cold and hot streams, leading to adverse impact on the turbine inlet temperature profile, which in turn, may reduce the Hot Gas Path (HGP) life by a significant amount.

To balance the two competing requirements, a Design of Experiments (DOE) approach was used define how best to prevent CO formation and understand the effect of several injection configurations on the turbine inlet profile. The dilution air injected inside the transition piece was split into three injection planes, FWD, MID and AFT as shown in Figure 8, and the dilution flow splits between those planes were swept from a min to a max number. The DOE included five cases, the four corner cases and the central point as shown in Figure 9.

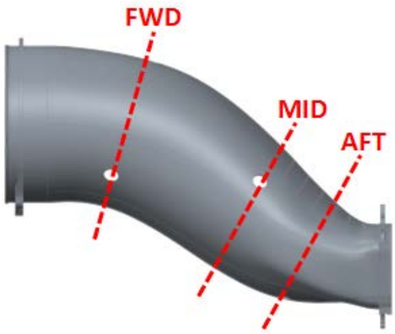


Figure 8. FWD, MID and AFT dilution planes along the transition piece

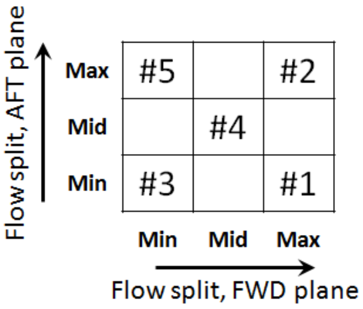


Figure 9. DOE cases definition

For each of those five cases, Computational Fluid Dynamics (CFD) was run to understand the mixing and dilution of the dilution air inside the transition piece, and the impact on the turbine inlet temperature profile. Figure 10 gives an overview of the CFD model that was used while Figure 11 shows a representative turbine inlet temperature profile of one of the cases obtained with CFD analysis.

It was well understood that case #5 was going to generate the least amount of CO but will have the poorest turbine inlet temperature profile while case #1 was going to generate the most amount of CO but will potentially have the best turbine inlet temperature profile.

Final configuration was similar to case #3, which was the best compromise between acceptable expected CO level and a turbine inlet temperature profile with no discernable HGP life impact.

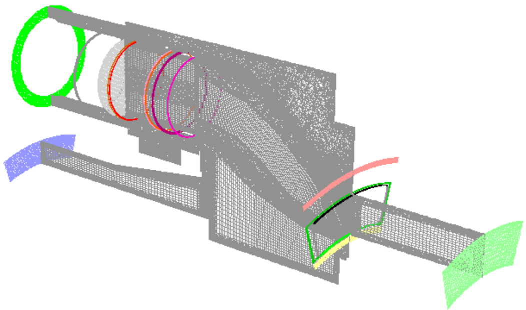


Figure 10. Overview of the CFD model, about 20 million elements

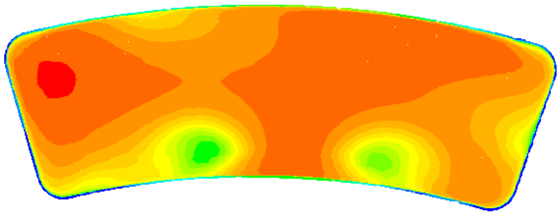


Figure 11. Representative turbine inlet temperature profile

Flashback strategy

Standard production 7EA ultra low emission combustion system hardware was going to be sized and procured for the conversion. Though some dilution and mixing holes in the liner and transition piece are custom sized for each application, other features key to the operation principle of the ultra low emission combustion system are not, such as the venturi throat geometry.

The compressor pressure ratio for the 7B is significantly lower than that of the 7B/E, 7E or 7EA which decreases the density of the mixture at the throat and has a positive (increasing) impact on the throat velocity from a flow-function standpoint.

Preliminary calculations based on engine data and flow models showed that the lower compressor pressure ratio was balancing the lower mixture flow and that the velocity at the throat, hence margin to flashback, was going to be similar to past experience.

5. Results

The retrofit and commissioning of the first unit, occurred in June 2014, the second and third units were completed in October 2014 while the fourth and last in January 2015.

The new ultra low emission combustion system lowered oxygen corrected NOx emissions from 35 ppm to around 3 ppm across the desired gas turbine operating range while CO emission was reduced from up to 100 ppm with the old water injected diffusion system to 9-25 ppm. Figure 12 shows typical emissions and combustion dynamics levels across the premix operating range from Base Load to as low as 78%

load while Figure 13 is showing emissions vs ambient temperature for a few days of operation.

The characteristic combustion dynamics tones, the “Hot Tone (HT)”, “Cold Tone (CT)” and “Lean Blow Out (LBO)” tone that are monitored to ensure maximum combustion stability and durability of the system. Each were within their respective maximum allowable levels.

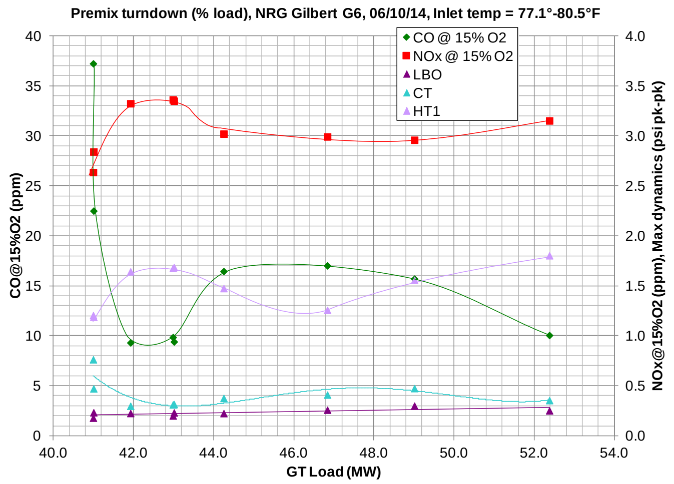


Figure 12. Emission and Dynamics Results with LECIII®

Combustion System as a function of load

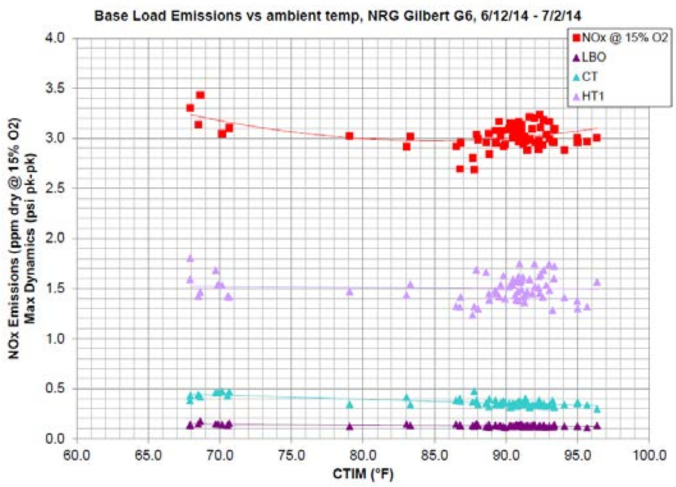


Figure 13. Emission and Dynamics Results with LECIII®

Combustion System across ambient

While the results are more than satisfactory for the 1st unit, a final modification to the transition piece dilution hole sizes will be done for the last three units. It shall bring NOx up to 4 ppm while CO is expected to be in the single digit range.

6. Conclusions

Emissions regulations, such as EPA Clean Power in the US and BLIERS in Canada are forcing Power Plant operators to make emission reduction decisions. In each case it is critical to analyze any number of technology solutions to ensure their business requirements and objectives are met. While the LECIII® is a product solution for the 7B/E, 7E and 7EA low emissions market, developing and implementing a similar design for older, low-firing gas turbines has opened a brand new market by keeping these assets economically & environmentally viable to the end customer.

The results from the conversion efforts detailed in this paper as well as current field experience at other end user sites with this type of technology installation shows the LECIII® system has the ability to achieve sub-4ppm NOx emissions with margin across the entire load range with acceptable levels of dynamics with extended combustion inspection intervals up to 32k fired hours. Furthermore, designed implementation was able to demonstrate a positive trade-off between achieving low CO emission through "late" dilution with no impact on HGP life.

As described above, these systems are available and operating within General Electric Frame 6B, 7B/E/EA and 9E machines on close to 70 gas turbines as well as two W501D5 and four W501B6 units, having accumulated over 1.5 million hours of successful operation.

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