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E-CLASS DLN TECHNOLOGY ADVANCEMENTS, DLN1+

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ABSTRACT

In the 1990s, GE's Dry Low NOx (DLN) technology helped E-class industrial gas turbines with the DLN1 combustor achieve single-digit NOx emissions. Today more than 730 DLN1 systems are installed worldwide. Recent advances in the technology achieve ultra-low single-digit NOx emissions well below 5 ppm. This paper summarizes the development history of DLN1, the operating experience of DLN1 and the recent technical advancements made to enable DLN1+ to achieve low single digit NOx emissions on 7E and 6B engines. Field validation performance results of the systems in commercial operation will be shared as well as a summary of fuel-flexibility results for the DLN1 and DLN1+ systems.

NOMENCLATURE/ACRONYMNS

CFD	Computational Fluid Dynamics
CLEC	Closed Loop Emissions Control
CPC	Corrected Parameter Control
DLN	Dry Low NOx
FEA	Finite Element Analysis
FFH	Factored Fired Hours
FFS	Factored Fired Starts
HCF	High Cycle Fatigue
IBH	Inlet Bleed Heat
LBO	Lean BlowOut
LCF	Low Cycle Fatigue
MNQC	Multi-Nozzle Quiet Combustor
MWI	Modified Wobbe Index
SCR	Selective Catalytic Reduction
TP	Transition Piece

INTRODUCTION

Since the early 1970s when emission regulations were introduced, gas turbine manufacturers have been providing combustors that meet domestic and international environmental agency regulatory demands for lower emissions. Nitrogen oxides (NOx) were and are the key components regulated. Low emissions expertise has evolved, and continues to evolve, through research, analysis, and testing.

When the first emissions regulations were introduced, GE combustors used a single fuel nozzle with a diffusion flame, which is inherently stable over a wide temperature range. However, since this design produces high NOx emissions, it could not meet the regulations. Combustion occurring at or near stoichiometric mixtures (when there is just enough fuel to react with available oxygen) caused these high NOx emissions. Figure 1 shows the flame temperature of distillate versus equivalence ratio. This ratio is a measure of combustor fuel-to-air ratio normalized by stoichiometric fuel-to-air ratio. Stoichiometric conditions are reached at the equivalence ratio of unity, and the flame temperature is highest at this point. For equivalence ratios of less than 1, the combustor is “lean”. For values greater than 1, the combustor is “rich”. The figure also shows a sharp rise in thermal NOx as the stoichiometric flame temperature is reached. Away from this point, thermal NOx production decreases rapidly. Reducing flame temperature is the best way to control thermal NOx in a diffusion flame combustor. [4]

Therefore, starting in 1973, water and steam injection were used to reduce flame temperature, which resulted in reduced NOx emission levels. The GE Multi-Nozzle Quiet Combustors (MNQC) was introduced in 1988 to improve combustor performance. MNQC also uses a diffusion flame with diluent injection to meet the continued restrictions in emission levels, but it accomplished this reduction while reducing the detrimental effects to the gas turbine cycle performance, operational cost, part lives, and inspection criteria that result from simply increasing steam and water flow on a single nozzle combustor.

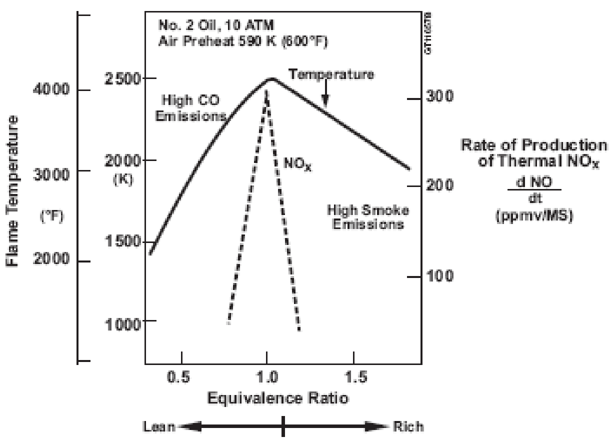

Figure 1: NOx and Flame Temperature

In preparation for the market's need for lower emissions, manufacturers began to develop lean pre-mixed combustion systems. GE began aggressively developing lean pre-mixed or DLN technology to replace diffusion combustors in the 1970s. The push for DLN technology was driven by its ability to provide low emissions without the need for costly diluent injection or Selective Catalytic Reduction (SCR) systems. DLN technology also has lower NOx potential compared to a diffusion flame, which is important for meeting continued regulatory restrictions. DLN technology provides lower emissions by operating with leaner flame fuel-to-air ratio (equivalence ratio < 1.0) compared to a diffusion combustor. Figure 2 shows a general comparison between diffusion and DLN combustors.

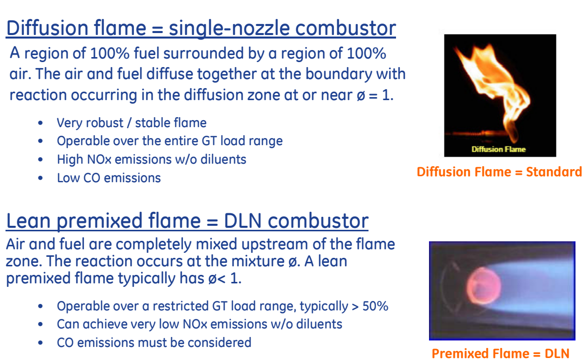

Figure 2: Flame Types

Developing a lean pre-mixed combustion system was a significant technical challenge because numerous parameters or boundaries needed to be satisfied. Figure 3 illustrates combustor operational space. For the purposes of this conversation, inside the box represents successful combustion operation, and outside the box represents unsuccessful operation that happens because one of the box boundaries has been violated. The key boundaries (sides of the box) are NOx, CO, dynamics (combustion noise), Lean Blow Out (LBO) or stability, and hardware durability (ensures successful operation between inspection intervals). The development challenge was to identify and implement hardware technologies/features and operational methods (i.e. fuel and air control) that provided a large box for the combustor to operate within while at very low emissions levels.

As NOx was lowered during development, the operational space inside the box shown in Figure 3 become smaller and improvements to the other sides of the box were needed in order to maintain the necessary operational space. Other challenges arise because improvements to each side typically cause the other sides to move inward, further reducing operational space. This was why extensive research, analysis, and testing were crucial to providing a large operational space at very low emissions.

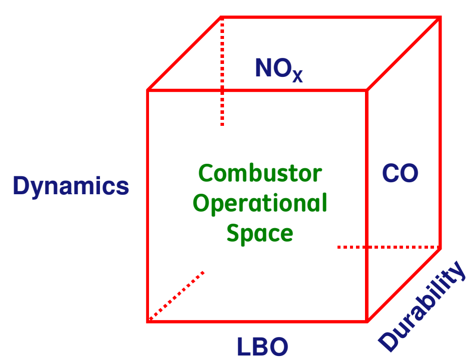

Figure 3: Operational Boundaries

DLN1 HISTORY, TECHNOLOGY, AND EXPERIENCE

DLN1 History

The original DLN technology from GE designated DLN1, was developed for E-class gas turbines. Following the first field tests in Houston (1980), the technology was further developed to meet tighter emissions regulations. The first commercial DLN1 combustion systems for natural-gas-fired heavy-duty gas turbines were introduced in 1991. Originally designed for 7E and 6B frame turbines, the technology was subsequently applied to 7EA, 9E, 52D, 51P, and 32J frame types. Within the last five years, newer technology capable of achieving well below 5 ppm

NOx levels was introduced as DLN1+. Additional performance improvements are under development today.

Figure 4 highlights DLN1's previous and ongoing progression to lower NOX levels.

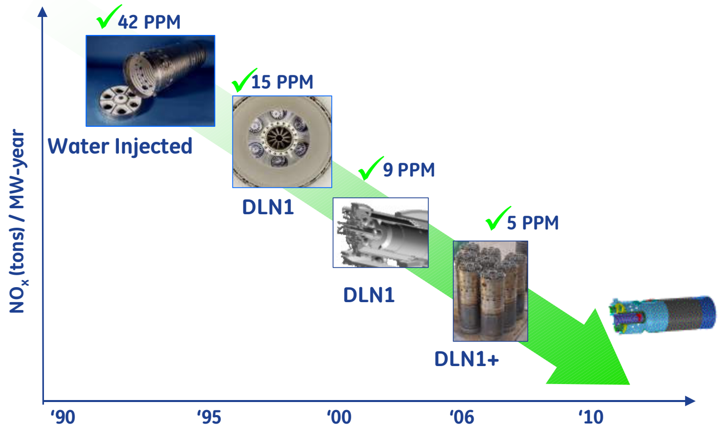

Figure 4: NOx Progression

DLN1 Technology

The DLN1 combustor is shown in figure 5. The combustor is made up of five major components: secondary fuel nozzle, primary fuel nozzles, liner, venturi, and cap/centerbody assembly. These components define the volumes and provide the fuel needed for the four modes of operation.

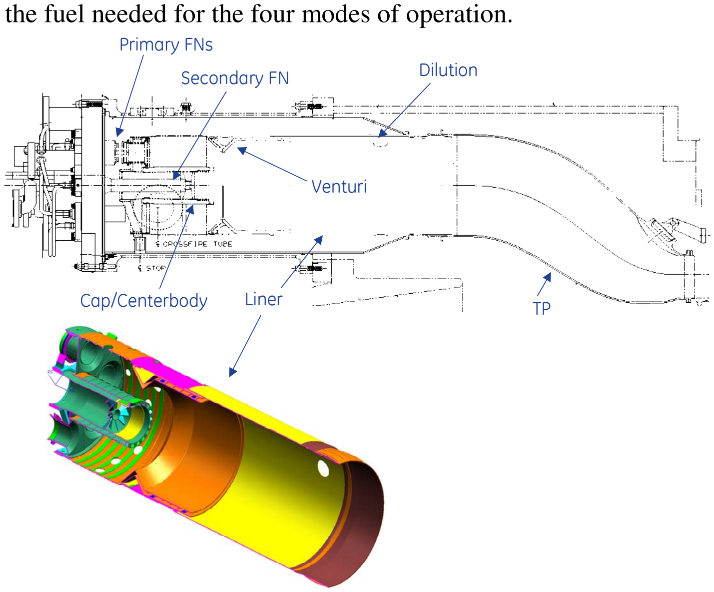

Figure 5: DLN1 Combustor

Figure 6 shows the four DLN1 operational modes that are needed to go from ignition to baseload pre-mix operation. The description for each is included below [1].

Primary mode

Only primary nozzles are fueled. Flame is in the primary zone only. This mode of operation is used to ignite, accelerate, and operate the machine over low- to mid-loads, up to a pre-selected combustion reference temperature.

Lean-Lean mode

Both the primary and secondary nozzles are fueled. Flame is in both the primary and secondary zones. This mode of operation is used for intermediate loads between two pre-selected combustion reference temperatures.

Secondary mode

Secondary nozzle only is fueled. Flame is in the secondary zone only. This mode is a transition state between lean-lean and pre-mix modes. This mode is necessary to extinguish the flame in the primary zone, before fuel is reintroduced into what becomes the primary pre-mixing zone.

Pre-mixed mode

Both the primary and secondary nozzles are fueled. Flame is in the secondary zone only. This mode of operation is achieved at and near the combustion reference temperature design point. Enhanced emissions are generated in pre-mixed mode.

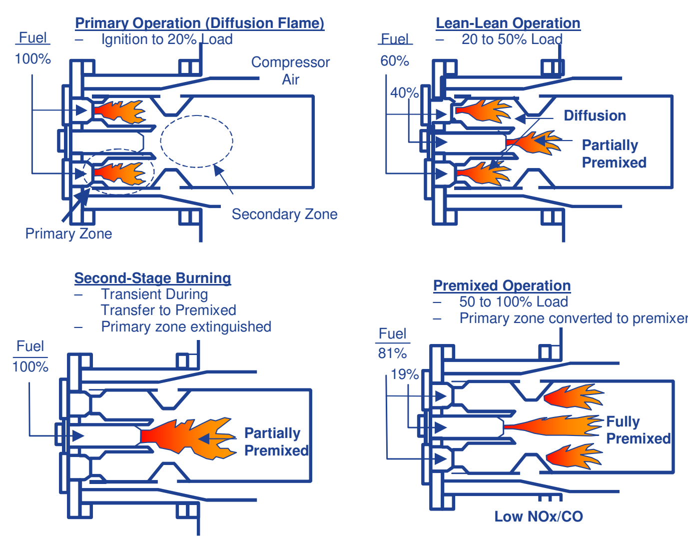

Figure 6: DLN1 Modes of Operation

Key DLN1 combustion features make low NOx possible during the pre-mixed mode of operation. The primary zone is an efficient pre-mixer that provides lean fuel/air ratios critical for low NOx. The downstream side of the venturi provides a stable location in the secondary zone for one of two pre-mixed flames.

The venturi also keeps throat velocity sufficiently high to prevent re-ignition in the primary zone during pre-mixed operation so that pre-mixed operation is maintained. The second pre-mixed flame in the secondary zone is located downstream of the secondary fuel nozzle, and it provides pre-mixed combustion and stability to the secondary zone. The fuel nozzle provides both a pre-mixed mixture of fuel and air for low NOx and a small amount of piloting fuel for stability. Finally, the liner dilution hole spacing and location were defined to provide CO burnout (reduction) and good combustion exit temperature profiles, which affect turbine hardware life.

DLN1 Experience

GE's extensive Frame 6, 7, and 9 total operational experience thorough October 2009 is summarized in Table 1 along with DLN1 unit count for the different frames.

Table 1: Experience

Frame	Total Units	DLN1 units	Total Fired Hours
6B	1030+	190+	60M +
7B/E/EA	1100+	375+	30M +
9E	600+	135+	23M +

Figure 7 summarizes DLN1 experience on B/E-class units. Specifically there are over 730 DLN1 units with more than 23 million fired hours of operation. The DLN1 capability for frame 6, 7, and 9 is from 15 to 9 NOx over a wide load and ambient gas turbine operational range.

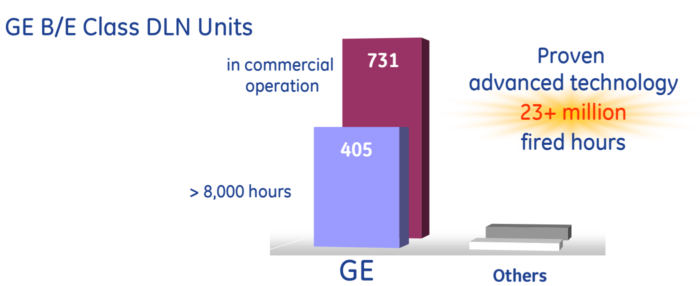

Figure 7: DLN1 Experience

DLN1+ HISTORY, TECHNOLOGY, AND EXPERIENCE

DLN1+ History

The DLN1 technology on E-class turbines has been enhanced to help satisfy changing government regulations and/or business needs for reduced emissions and to eliminate costly diluent injection or SCR systems. This enhanced combustor (DLN1+) builds on years of DLN1 experience. DLN1+ development for lower emissions, down from the 7E/EA DLN1 9 ppm NOx level, began in late 2002. A successful field test of the DLN1+ 5 ppm combustor occurred at the end of 2005. This combustor is capable of achieving 5/25 ppm NOx/CO levels over a wide load and ambient range similar to DLN1.

DLN1+ development efforts continued aggressively when one customer needed help to meet a 3 ppm NOx regulatory requirement on eight units by the end of spring 2008. A development partnership resulted, providing access to field tests and continued prototype operation that validated each critical technology for both operability and durability. This development strategy made it possible to successfully implement the new DLN1+ combustor on all eight units operating below regulatory requirements by spring of 2008.

Since DLN1 has significant experience and success in the field, the overall development strategy was to keep the DLN1 configuration and apply advancing technologies to it. Engineers progressed through key phases to take advancing technologies from concept to final design.

In the first development phase, over 100 concepts were generated by using new technologies and leveraging features from F-class combustors with extensive DLN experience. Some concepts represented complex changes to DLN1 while some represented simpler changes. The engineers then applied analysis, testing, and engineering expertise to compare and identify the top concepts.

In the next phase, engineers defined these top concepts in greater detail and analyzed them more thoroughly with design computations including hand-calculations, Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) and with component testing to ensure that these concepts would prove to be operable and durable in future lab and field tests. Analysis was used to optimize concepts for High Cycle Fatigue (HCF), Low Cycle Fatigue (LCF), oxidation, wear, and dynamic response capability.

Once confirmed and improved by the previous steps, the top concepts were manufactured and lab tested in this third phase of development. Frame 7 gas turbines have 10 combustion chambers; and concept lab testing was performed on one combustion chamber at gas turbine operating conditions. The test facility delivered the pressure, temperature, fuel and airflows encountered in the gas turbine. In addition, combustion performance was mapped over the entire gas turbine ambient temperature and load range by varying inlet airflow conditions. Lab test results validated the analytical predictions and demonstrated that the concepts were operable and durable.

In the forth phase, concept technologies that successfully lab tested were combined into one configuration. Drawings were then created, and a hardware set was manufactured, installed, field tested, continuously operated and monitored on a gas turbine. The field test and continuous operation validated the operability and durability of the concept's technologies. It also identified changes for future improvements.

Six different demonstration field tests were performed throughout the DLN1+ effort. This was made possible by conducting the first three development phases (conceptualizing, design and analysis, and lab testing) simultaneously with field testing and operation, therefore providing a steady stream of concepts for field tests. The results and experience from all field tests validated the final design implemented on the units.

DLN1+ Technology

Figure 8 shows the key Frame 7 DLN1+ design features that provided the emissions, operability, and durability performance. These features work together to simultaneously provide low NOx and a wide operational volume. This was accomplished by implementing technologies that reduced emissions, shrunk can-to-can variation, and improved margins to operational boundaries.

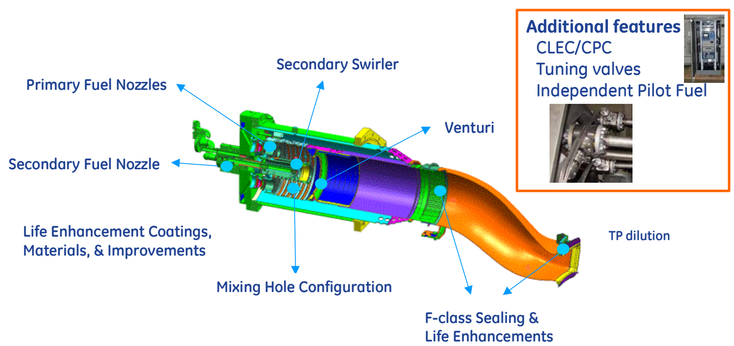

Figure 8: Frame 7 DLN1+

Life Enhancements and Sealing

Liner two-cool hula seal, transition piece (TP) aft-end integral mount, and TP cloth seals are demonstrated F-class technologies applied to the DLN1+. The TP mount enhances hardware durability while the seals reduce airflow variation resulting in tighter fuel/air control that minimizes emissions variation.

Figure 9 shows the liner two-cool hula seal compared to the original DLN1 seal. Two-cool reduces airflow and variation due to improved hula seal arrangement along with a more effective cooling scheme. Leakage is reduced by overlapping the seal fingers. The cooling scheme reduces the seal operating temperature for improved durability. In addition, the hula seals are coated for extended wear life.

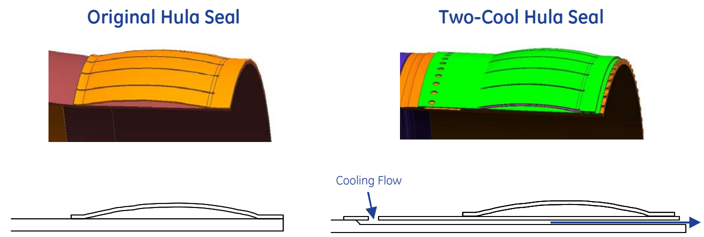

Figure 9: Two-cool Hula Seal

The new TP aft-end mount (Figure 10) is integral with the aft-frame and has two main durability advantages over the older tractor seat mount design. It eliminates the tractor seat to TP body weld and reduces stress in the body of the TP by having the loads transition more evenly from the skin to the aft mount.

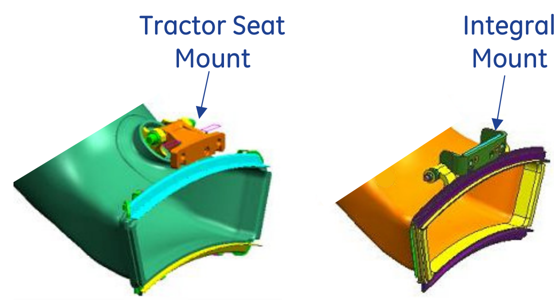

Figure 10: TP Aft-end Mount

The DLN1+ TP cloth seals as shown in Figure 11 are flexible and conform better to the receiving slot surfaces in the TP aft frame. They also provide more sealing contact compared to the previous hard seal design. As a result, leakage and its variation are reduced. In addition, the cloth seal provides longer life since it is made of wear-resistant material and sealing loads are shared over a larger contact area.

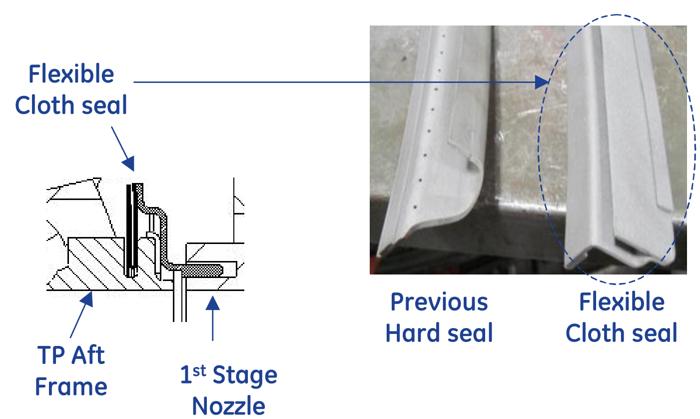

Figure 11: TP Cloth Seals

Life was enhanced with a new liner stop design along with the use of wear-resistant materials and coatings at key hardware interfaces. The liner stop design improves load distribution between stops for reduced wear and wear variation. Figure 12 shows a stop contact surface, which is representative of all liner stops after 11,167 hours of operation. The image shows light wear, which is only sufficient to polish the surface roughness at each contact location. The figure also shows how the stop is assembled into the flow-sleeve (body not shown for clarity) slot.

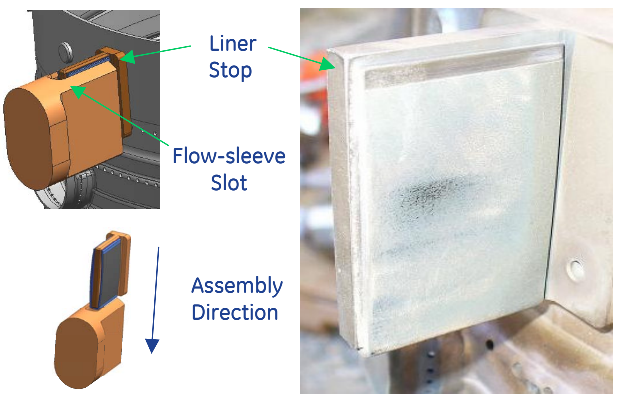

Figure 12: Liner Stop with Negligible Wear

Primary fuel nozzles

Primary fuel nozzle tips were improved to increase tip seal performance resulting in reduced emissions variation. The improved design provides a simplified and more robust assembly process that reduces assembly variations, which can affect tip seal performance. It also increases the maintainability of the fuel nozzle and endcover assembly.

Secondary fuel nozzle

In the DLN1, the pilot fuel is a fixed percent of secondary fuel flow. The DLN1+ fuel nozzle has independent control that allows the pilot fuel flow to be varied for the best balance between lower NOx and good combustion operability. The DLN1+ secondary fuel nozzle also has improved sealing that decreases both NOx emissions and variation. The new seals reduce leakage and variation (standard deviation) relative to the existing DLN1 seals respectively by over 74 percent and 63 percent. Figure 13 shows the probability distribution comparison between the new and existing DLN1 seals. Figure 14 shows how this improvement was obtained by redesigning the DLN1+ fuel nozzle to have compression style seals in place of piston ring seals in the DLN1. The new seals provide more contact pressure, which results in better sealing.

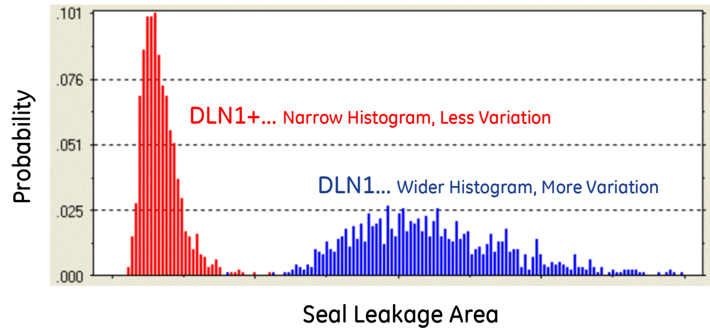

Figure 13: Fuel Nozzle Seal Leakage Area

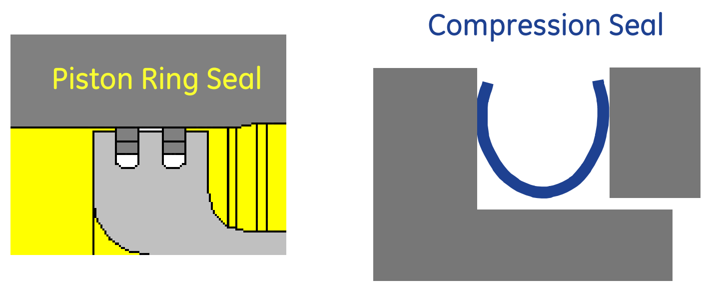

Figure 14: Fuel Nozzle Seal

Corrected Parameter Control (CPC)

Corrected Parameter Control (CPC) modulates fuel and airflow to accommodate humidity, turndown, and ambient effects on combustor performance. The CPC algorithm employs physics-based models of combustion boundaries and GT performance. In this model-based control scheme, the logic is set to choose the fuel split (fuel fraction between fuel circuits) that provides the best operation within operability boundaries, regardless of fuel composition. This allows the combustor to operate with emission compliance in a larger operational turndown (load and ambient) envelope.

Closed Loop Emissions Control (CLEC)

Closed Loop Emissions Control (CLEC) provides the ability to continuously tune the CPC model with real-time emissions measurement resulting in the unit's ability to auto-tune. This reduces emissions variation and provides an additional widening of the operational envelope already widened by CPC alone. It also eliminates seasonal retunes. The basic strategy for CLEC is to use emissions data from the customer CEMS as the feedback to the gas turbine controller. Figure 15 shows how tightly emissions are controlled over several months of fielded GT performance. Figure 16 shows baseload operating points over a wide ambient temperature range covering 14 months of operation.

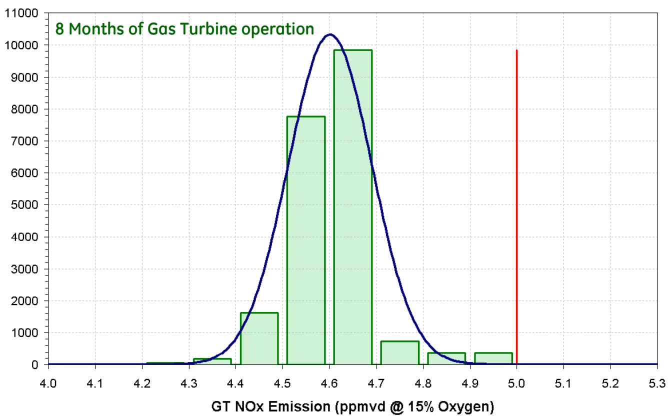

Figure 15: Field NOx Variation

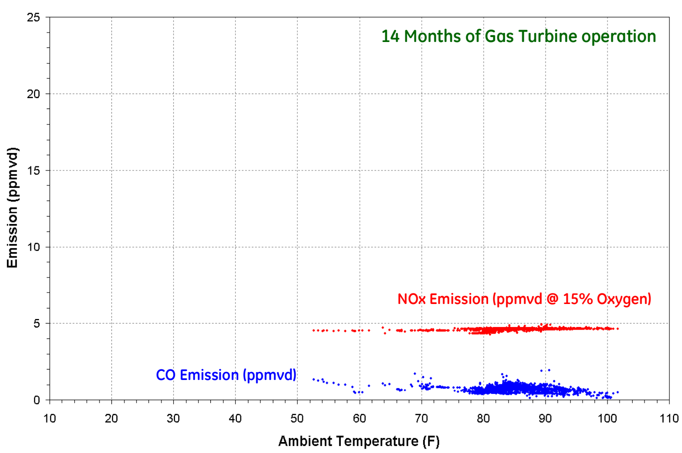

Figure 16: Ambient Performance

Can Level Tuning Valves For Primary Fuel

A significant influence on gas turbine emissions is can-to-can variation due to hardware tolerances, flow path geometries, and assembly tolerances. This variation has been reduced with the design improvements previously described, and it continues to be improved in ongoing development efforts. Since not all variation can be eliminated, can-level fuel control is used. Adding tuning valves to the primary fuel circuit accomplished this control. These valves are used to enhance chamber-to-chamber air/fuel reducing CO emissions. The tuning process is performed during unit startup following a CI, and final valve positions remain unchanged until the next CI.

Venturi

Similar to DLN1, the DLN1+ combustor has two distinct flames. The interaction between the two flames is very important for emissions, stability, and dynamics. This interaction is affected by numerous factors including those related to the venturi: cooling flows through the centerbody, expansion of the primary zone flow past the venturi, size and location of the venturi, and shape of the venturi. These parameters were enhanced during the DLN1+ development effort for lower emissions performance.

Premixing

The primary zone has six fuel nozzles (Frame 7) that consist of an air swirler with fuel injection holes very close to the exit of the fuel nozzle. Jets of air from holes in the liner then act upon the mixture coming out of the fuel nozzles. This process accomplishes pre-mixing in the primary zone. To enhance pre-mixing, one can either improve the primary nozzles or redesign the holes on the liner to achieve a target fuel distribution. The latter approach was one of the strategies employed in DLN1+ combustors [2]. It is to be noted that more pre-mixing does improve NOx, but this improvement must be balanced against impacts that can typically occur to the other boundaries of the operational space (CO, dynamics, and stability). DLN1+ pre-mixing performance was improved and combined with other technologies to provide this balance.

TP dilution [2]

NOx and CO emissions depend on the time and temperature history of the flow. Figure 17 shows the temperature profile inside a DLN1+ combustor. Flow is from left to right [6]. Red indicates higher temperatures while blue indicates low temperatures.

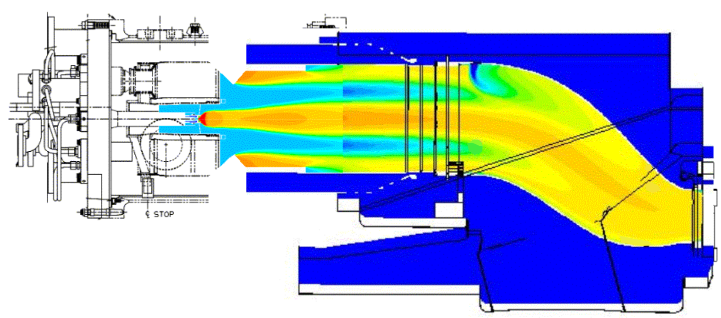

Figure 17: DLN1+ Temperature

Appropriate management of dilution air is very important for tailoring the temperature profile inside the combustor. The introduction of dilution flow too early in the combustion process can result in high CO emissions, but delaying the introduction of dilution flow could increase NOx emissions. In addition, the dilution flow must be introduced in such a manner that it can mix with the hot gases and result in a combustor exit profile acceptable to the hot gas path.

Figure 18 shows the results of a study carried out to determine the best balance of the combustor temperature profile. In addition to NOx/CO, the chart has two additional axes – reaction zone residence time and aft zone gas temperature. A low reaction zone residence time indicates that at least a portion of the dilution air is injected axially closer to the combustor flame zone. A low aft zone gas temperature indicates how much dilution air is introduced closer to the flame zone. The surface is colored to be representative of NOx at a fixed CO level. The shape of the surface shows that there is an ideal way to position and size the dilution holes and that this definition has to be carefully engineered using CFD and experiments [2].

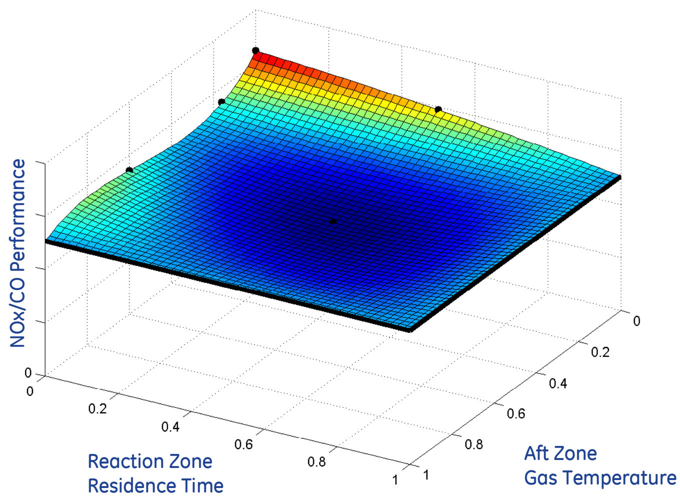

Figure 18: Emissions Map

Data from more than six lab tests finalized the NOx/CO surface shape shown in Figure 18 and defined the dilution pattern in the hardware. CFD provided insight on both emissions and exit temperature profile for dilution hole configurations. Figure 19 is a view looking upstream of combustor flow. The view shows CO emissions profile from CFD analysis [6] at the exit of the TP where higher levels are represented by the light blue to green colors.

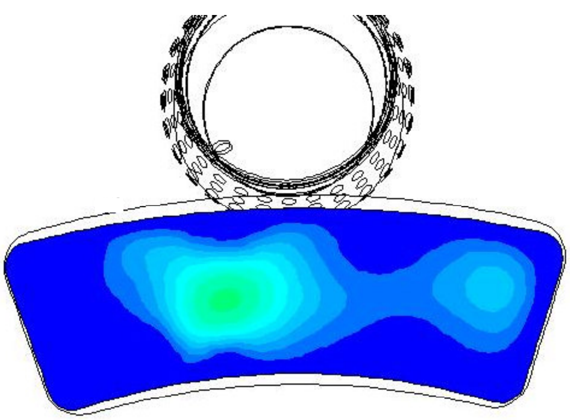

Figure 19: CO Emissions

Secondary fuel nozzle swirler

The secondary fuel nozzle swirler is important to the overall emissions performance and stability of the combustor. As mentioned above, the flame just downstream of the secondary fuel nozzle is one of two flames in the secondary zone. Since both flames in the secondary zone strongly interact, the swirler affects both pre-mixed flames. The DLN1+ development effort introduced an improved swirler for enhanced performance.

DLN1+ technology was also developed for 6B gas turbines. During this effort, many frame 7 DLN1+ features were leveraged into the 6B design along with its own unique features. The resulting 6B design was successfully field tested in April 2008, and continues to grow its operational experience. Figure 20 shows key features for 6B DLN1+ and how many of these features are similar to frame 7 DLN1+.

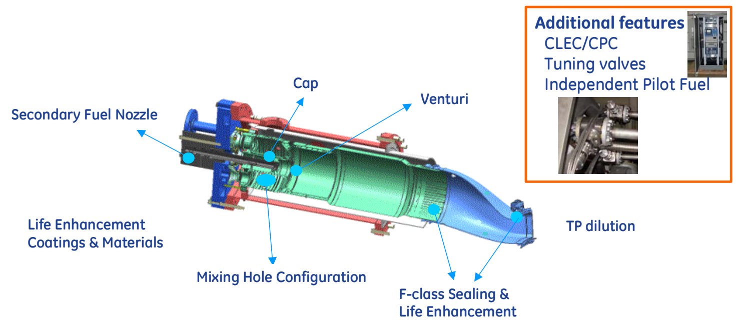

Figure 20: Frame 6 DLN1+

Detailed definition, analysis, and testing were also performed during 6B DLN1+ development. Figure 21 shows venturi and liner metal temperatures from 3D CFD analysis [6]. These results were validated against lab test measured thermocouple and thermal paint temperatures. With CFD results as input, FEA models were then used to optimize the design for High Cycle Fatigue (HCF), Low Cycle Fatigue (LCF), oxidation, creep, and dynamic response capabilities. These capabilities are being demonstrated in the field. This detailed analysis was performed on the 7EA and 6B DLN1+ components including the TP, liner body, venturi, cap, and secondary fuel nozzle.

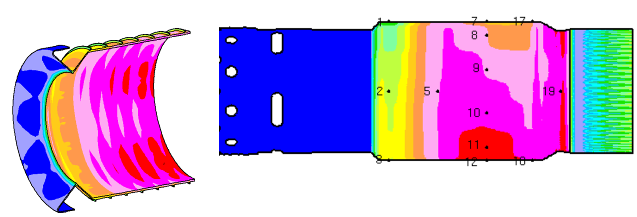

Figure 21: Venturi & Liner Temperatures

Figure 22 shows displacements for the first natural frequency mode from FEA [7] where red and blue colors are respectively maximum and minimum displacements.

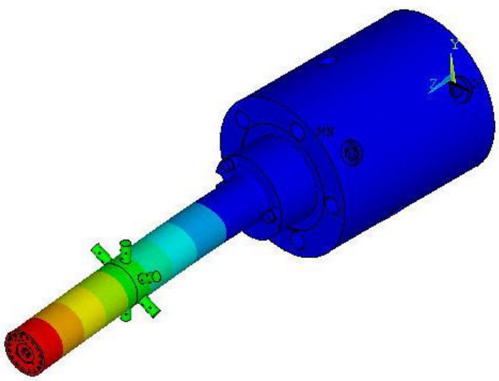

Figure 22: Secondary Fuel Nozzle Modal Analysis

DLN1+ Experience

Operational Time

Since the introduction of DLN1+ in 2005, the total DLN1+ fleet of 17 units has accumulated significant operational experience with more than 240,300 fired hours and 1,160 starts.

Since its introduction in spring 2008, the next generation of 7E/EA DLN1+ has continued to gain operational experience running to a 3 ppm air-permit on eight units with 103,000+ fired hours.

This next generation DLN 1+ combustion system allows for flexible emissions offerings depending on needed operating conditions, environmental considerations, and cost requirements. Different options are available for NOx emissions, from 4 ppm to lower levels while maintaining less than 25 ppm CO over a wide turndown envelope as noted in the "Turndown" section.

The DLN1+ combustor was designed for a combustion inspection interval of 24,000 Factored Fired Hours (FFH) and 450 Factored Fired Starts (FFS). Successful inspections on numerous units including the fleet leader at over 11,000 hours are demonstrating the design's 24,000 FFH combustion inspection interval capability.

Since its introduction in April 2008, 6B DLN1+ has continued to gain operational experience on a unit in Texas with more than 23,000 fired hour well below 5 ppm requirement.

Similar to 7EA DLN1+, flexible emissions offerings are available. Emission levels down to 4 ppm NOx are possible with very good turndown. In addition, impressive results from the hardware inspection at 9,000 fired hours show that the design is well on its way to demonstrating 24,000 FFH combustion inspection interval capability.

DLN1+ development continues for even lower NOx performance over a wide turndown range with 24,000 FFH combustion inspection interval capability.

Turndown

The chart in Figure 23 shows a typical shape of turndown capability for DLN1+ combustion systems. Turndown is the ability to stay below emission (typically NOx and CO) limits over a range of ambient and gas turbine load conditions. This emissions compliance appears as an area on the chart shown. In addition, the gas turbine configuration can significantly affect the turndown area shape and size. Having inlet bleed heat (IBH) and a higher exhaust temperature limit significantly increases turndown capability. IBH allows for more gas turbine airflow control requiring less change in combustion flame temperature, which maintains low emissions. Higher exhaust temperature capability provides more load reduction before reaching the exhaust temperature limit.

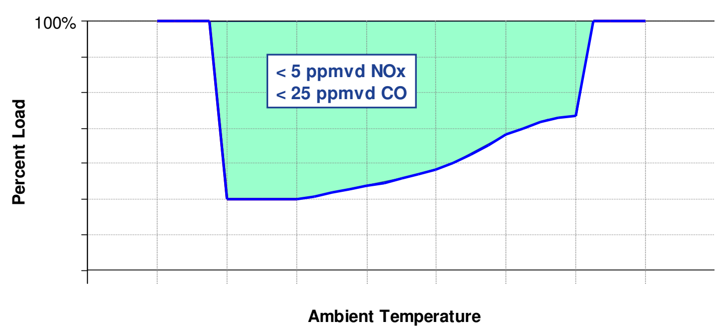

Figure 23: Turndown Capability

Since turndown is affected by multiple factors, a chart is needed to fully define it. Turndown capability cannot be adequately represented with a simple statement or number. For example, stating "50 percent turndown capability for single digit NOx and CO" does not provide a complete answer. This statement does not show capability at various ambient conditions and for different gas turbine configurations.

Figure 24 shows the DLN1+ 5 ppm combustor performance at a variety of load conditions. These measurements were taken at an 83 F ambient condition, therefore it would represent a single ambient slice of the chart similar to the one shown in Figure 23. The first observation is that NOx emissions are maintained below 5 ppm across all load conditions. Moreover, due to the design improvements and the tight accuracy and control by CPC and CLEC, there is very little variation in the NOx level resulting in very predictable NOx emissions. The second thing to note is that CO levels are very low – below 2 ppm – across most of the load range. This demonstrates the excellent CO capability of this combustor. Thirdly, it can also be seen that CO levels only increase after the exhaust isotherm limits the gas turbine exhaust temperature. The DLN1+ systems have turndown capability over a wide load and ambient range. Capability is from 0 to 120 F and down to 50 percent load. Developers continue to work on demonstrating capability down to extreme low ambient temperatures, -40 F.

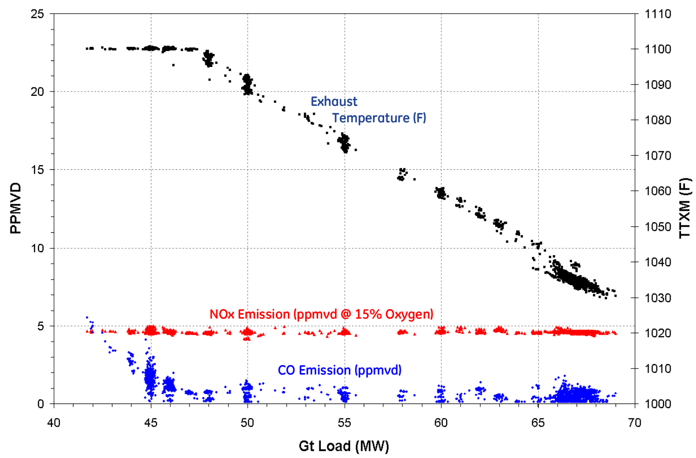

Figure 24: DLN1+ 5 ppm Combustor Performance

The key challenge to providing low emissions turndown capability for DLN combustors is maintaining the lean fuel/air mixtures with sufficient margin to the operable boundaries previously mentioned. The lean mixtures produce low flame temperatures needed for low emissions. At lower loads, as fuel flow to the combustors decreases, the flame temperature will eventually approach and be restricted by one of the operational boundaries, which if ignored could result in boundary violation such as blow out or emissions non compliance. This behavior is in direct contrast to that of a diffusion flame combustor due to its inherent stability over a much wider operational envelope.

DLN1 & 1+ FUELS FLEXIBILITY

As DLN1 and DLN1+ combustion technology has evolved, so has the systems' capacity to operate on a much broader range of gas fuels with low emissions. This improved capability allows DLN-equipped gas turbines to be considered for applications in petrochemical processing and cogeneration, replacing less efficient steam boilers, or flaring of byproduct fuel gases. Engineers performed extensive testing of DLN1 and DLN1+ combustion designs operating on a wide range of fuel compositions on frame 6, 7, and 9 gas turbines. The fuel compositions tested include hydrogen, ethane, propane, butane, ethylene, and propylene.

In pre-mixed combustion for gas turbines, the following parameters are identified as critical: flashback margin, LBO margin, emissions, dynamics boundary margins, and hardware durability. All these are critical factors for successful operation with a wide range of fuels and they have been thoroughly investigated via lab and engine testing in the recent past. This accumulation of laboratory and field experience has provided a more detailed and complete understanding of the physics and chemistry behind the observed combustor performance.

Figure 25 shows experimental data taken for a DLN1 system for blends of reactive fuels, such as higher order hydrocarbons and hydrogen, and methane. Combustor operating conditions such as inlet air temperature, pressure and flow, as well as the exit temperature, were maintained while the concentration of reactive fuel in the fuel blend was increased. Figure 25 shows the increase in hot tone dynamic pressure amplitudes with an increase in reactive fuel, which could be a limiting factor in defining the acceptable dopant limit.

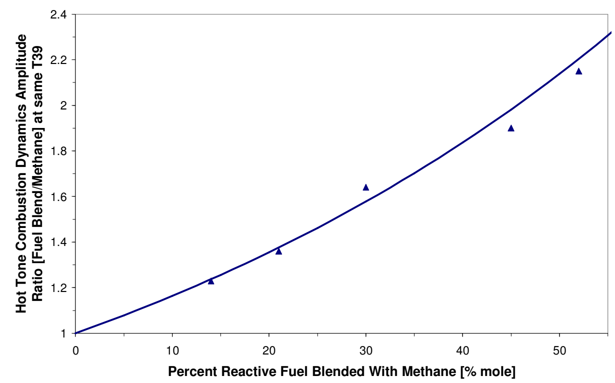

Figure 25: Dynamics versus Fuel Composition

Figure 26 shows from lab test data how the NOx increases with the addition of more reactive constituents. This chart expresses NOx ratio (reactive fuel/methane) versus reactive fuel to methane concentrations at a constant DLN1 combustor operating condition. The opposite trend is observed with the addition of inerts, such as nitrogen.

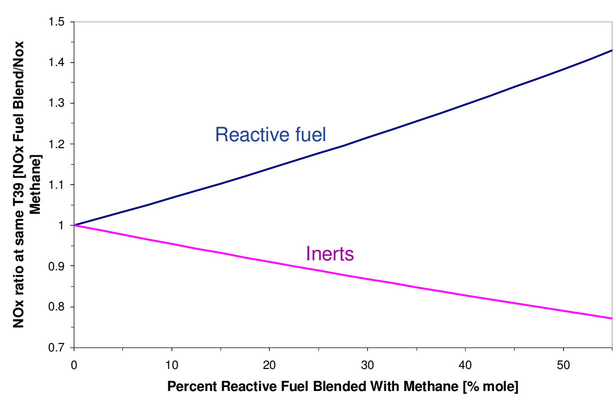

Figure 26: NOx versus Fuel Composition

Transfer functions linking fuel gas composition, combustion properties, combustor operating conditions, gas turbine parameters, and exhaust emissions have been developed and incorporated into the permitting process and control algorithms. These transfer functions allow a wider range of fuels to be considered for DLN operation, as well as a wider range of variation as the fuel supply composition varies from minute to minute and day to day.

Traditionally, an acceptable fuel composition variation for DLN gas turbines has been ± 5 percent Modified Wobbe Index (MWI). Today's better understanding of combustion performance and operability boundaries in a wider fuel space allows for a MWI variation of ± 15 percent from ignition to the fully loaded operation. For E-class DLN combustion systems in the pre-mix combustion mode, which is typically above 50 percent load, an even higher fuel composition variation is acceptable, up to ± 40 percent MWI on NG fuel. Reference [3] has more detailed information on fuel flexibility and capability.

It should also be highlighted that steam injection capability is available for DLN1+ with capability to 5 percent of W2 flow.

CONCLUSION

This paper details the development history of DLN1, the operating experience of DLN1 and the recent technical advancements made to enable DLN1+ to achieve low-single-digit NOx emissions on 7E and 6B engines. Technology development has progressed on these combustion systems from diffusion flame to DLN pre-mixed flame combustors producing much lower emissions. The latest DLN1+ system builds on vast DLN1 field experience since the DLN1 configuration was the starting point for development. This DLN1+ effort provided NOx emissions capability well below 5ppm by making improvements to DLN1, leveraging proven F-class features, and introducing new technologies.

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