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GAS TURBINE COMBUSTION SYSTEM RETROFIT SOLUTIONS ADDRESSING CANADIAN INDUSTRY'S NEED FOR INCREASED OPERATIONAL FLEXIBILITY

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Abstract

Gas turbines are currently operating in a wide variety of applications in the power generation industry. Increasingly, fleets are being pushed for greater operational and fuel flexibility, in order to better contend with today's difficult market conditions. Across Canada, the increase of renewable energy production is changing the traditional base load operation of gas turbines, in some locations pushing units to get online more quickly and maintain lower turndown rates while operating within increasingly stringent emissions limits.

PSM, a leader in developing innovative service solutions for operators of heavy duty gas turbines, has a portfolio of combustion retrofit solutions designed specifically to meet these market needs. Coupled with PSM's AutoTune and FlexSuite™ digital solution functionalities, combustors can reliably operate in a wider operating profile or with an increased fuel Modified Wobbe Index (MWI) range. Additionally, petrochemical plants facing restrictive flaring limits are looking for innovative ways to consume process off-gases such as hydrogen and doing so within a gas turbine cogeneration power plant is a perfect example. Looking to the future, the ability to burn hydrogen, in areas where excess wind capacity is used to generate hydrogen from water through an electrolysis process, could offer improved emissions, lower CO2 footprint, and access to a less costly fuel. PSM retrofit combustion technologies, LEC-III® and LEC-NextGen for the B- and E-class and FlameSheetTM for the F-Class, that burn high volumes of hydrogen will be reviewed. Results from an LEC-III conversion at a 9E facility that now runs 25% hydrogen will be shared. A recent installation of LEC-NextGen in Alberta, Canada area will be presented as well. This installation lowered emissions limitations, extended maintenance intervals, and is suited for potential fuel flexibility in the future with the addition of AutoTune without needing additional hardware change.

Introduction:

Energy and Market drivers; the Renewables' Penetration:

In the US, the gas turbine power generation market continues to face pressure from changing conditions in the power generation market due to fluctuations in electricity demand from natural gas and increasing penetration of renewable energy sources in the broader energy markets. According to the EIA's 2018 Energy outlook, there will be a net gain of ~60 GWe after accounting for new installations and retirements of natural gas fired gas turbine and combined cycle technologies through 2030 (1). As shown in Figure 1, the reference case has natural gas and renewables jointly displacing coal and nuclear energy sources in growth in the US electricity generation market. However, depending on resource and technology projections in oil and gas production, their relative market share can be significantly different – where either natural gas or renewables can take the lead over the other by a factor of up to ~200% by the year 2050.

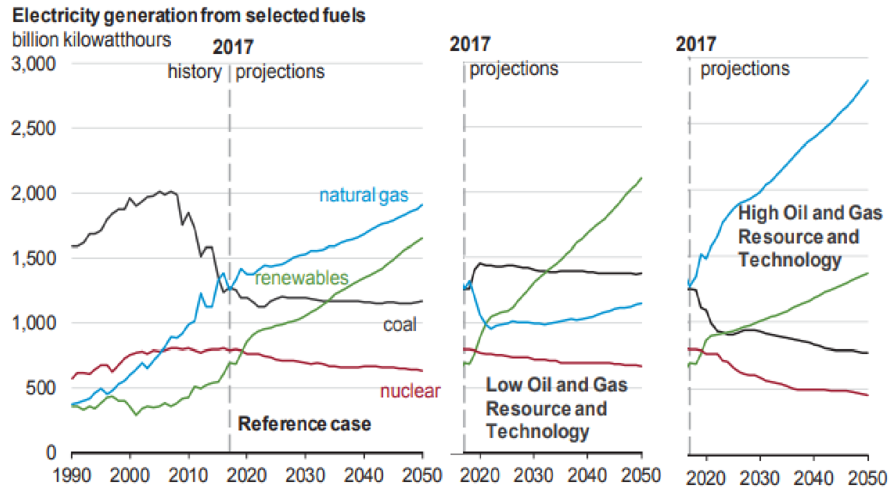

Figure 1: EIA Electricity Generation from Selected Fuels - Projections through 2050

A further challenge in the US with the introduction of renewables is the cyclic nature of swings in load demand due to short term weather changes as well as long term daily changes in solar and wind availability. The resulting swings in load demand can lead to the "ramping flexibility curve," also called the "duck curve," as reported by California ISO (CAISO) (2), Figure 2. The growing penetration of renewables brings higher levels of non-controllable and variable generation resources. CAISO must therefore ramp up the direct controllable resources, such as gas fired power plants, to match both variable demand and supply. In this environment, the window of profitable operation for natural gas turbines is effectively reduced to morning and afternoon/evening peaks.

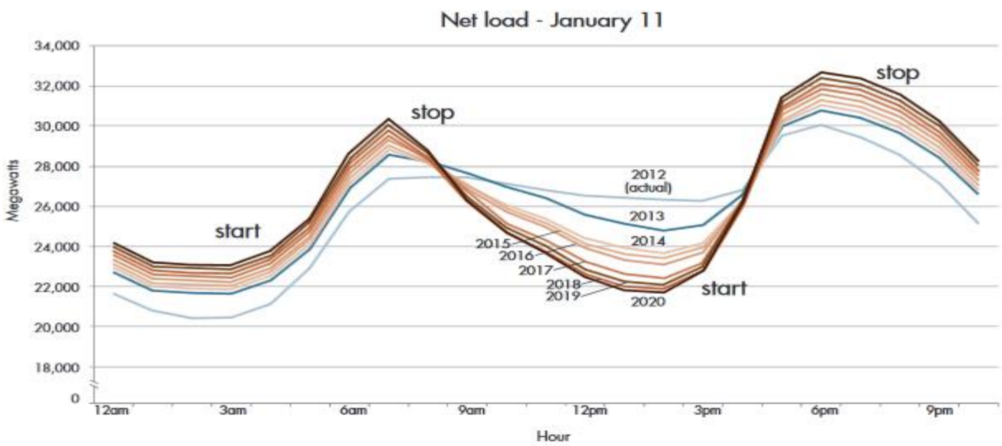

Figure 2: California ISO's Net Load for January 11

These competing demands on unit operation require an operationally flexible combustion system that can meet emissions at the two extremes: high NOx is a challenge for peak firing at higher loads, while CO generation becomes the limit for lower loads as the combustors must run at lean limits.

According to National Resources Canada [3,4,5], Canada, relies on Natural gas to provide 24% of its energy production and while Canada is the 4th largest Natural gas producer in the world, Canada imports ~ 2.5-3 Bcf per day of Natural gas from the US see Figure 3b below. In 2017, Canada imported **2.4 Bcf/d (0.07 Bcm/d)** of natural gas, and natural gas imports from the U.S. into eastern Canada are on the rise, due to higher supplies in the U.S. Northeast and shorter transportation distances from these U.S. natural gas basins.

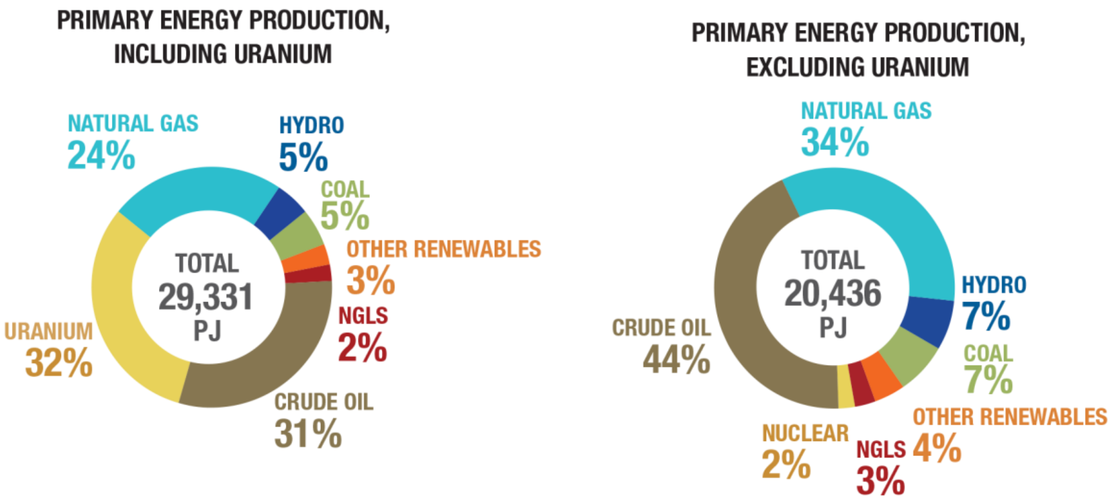

Figure 3a: Canada energy production by source

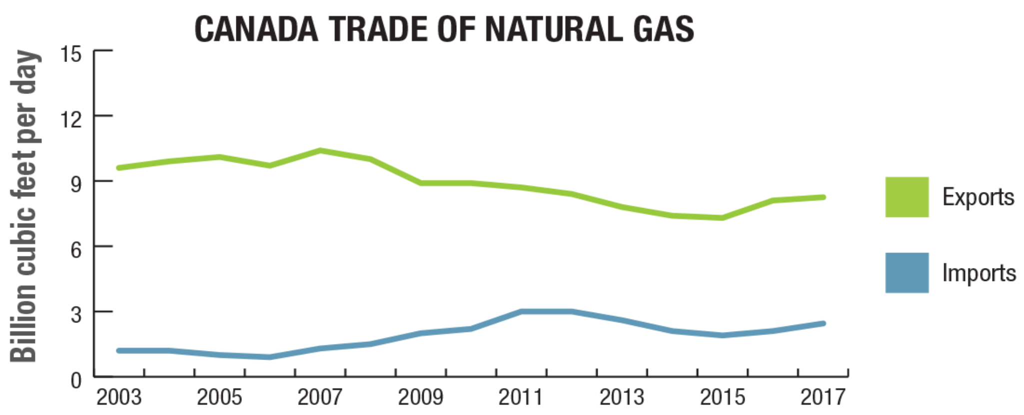

Figure 3b: Canada energy production by source

The Shale Gas Challenge:

Another US market driver for flexibility is the variation of natural gas constituents which is inherent in shale natural gas production in the US. While increased shale gas production has been credited for reduced NG (natural gas) prices in the U.S, it has also posed a challenge to the gas turbine power generation market due to variations in gas composition and heating value.

A normalized measure of fuel flexibility can be represented using the Modified Wobbe Index (MWI) which accounts for variation in fuel heating value and density, and is defined as follows:

$$\mathrm{MWI} = \frac{LHV}{\sqrt{(SG \times T)}}$$

LHV = gas lower heating value (BTU/ft^3)
SG = Specific gravity of fuel gas relative to air
T = Fuel gas absolute temperature (^{o}R)

The Modified Wobbe Index is affected by both fuel gas temperature and heating value of the fuel. It is possible to offset the effect of one of these parameters with the other to maintain the MWI within an acceptable range.

According to the EIA (U.S. Energy Information Association) [6], shale gas composition varies substantially from one shale gas region to another across the U.S.A. Calculated MWI variation based on the compositions can be as high as 78% see figure 4 below. The variation fuel composition can pose operational issues for low emissions premixed combustion systems in the form of emissions and combustion pulsations and stability, and as such a, a combustion system capable of operating with large fuel MWI variation can be an asset to gas turbine power plants.

Typical Shale Gas Constituent Ranges (% Volume)

	C1	C2	C3	CO_2	N_2	MWI Variation %
Barnett	80-95	2-12	0-6	0-3	1-8	-8%
Marcellus	79-86	3-17	1-4	0-1	0-1	-1%
Fayetteville	97	1	0	1	1	3%
New Albany	87-93	0-2	0-3	5-11	-	-21%

$$Modified\ Wobbe\ Index\ = \frac{LHV}{\sqrt{SGgas\ \times Tgas}}$$

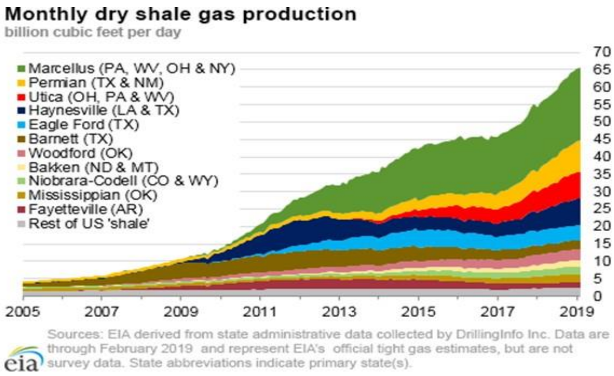

Figure 4: Shale gas production and constituents' variation in US produced shale gas

The De-Carbonization/Hydrogen Initiative:

In addition to fuel to the shale gas constituents' tolerance, the hydrogen initiative in the energy production has been making large strides in the recent years from a decarbonisation and green house gas reduction standpoint. The infiltration of Hydrogen use has been primarily seen in Europe, but this initiative has recently crossed the Atlantic and made its way into the US and likely in Canada. The greenhouse gas reduction initiative in Europe has generated tremendous political pressure to reduce and eliminate carbon based fuels and has been key in accelerating the Hydrogen economy and advancing the technology in that sector, see figure 5 below.

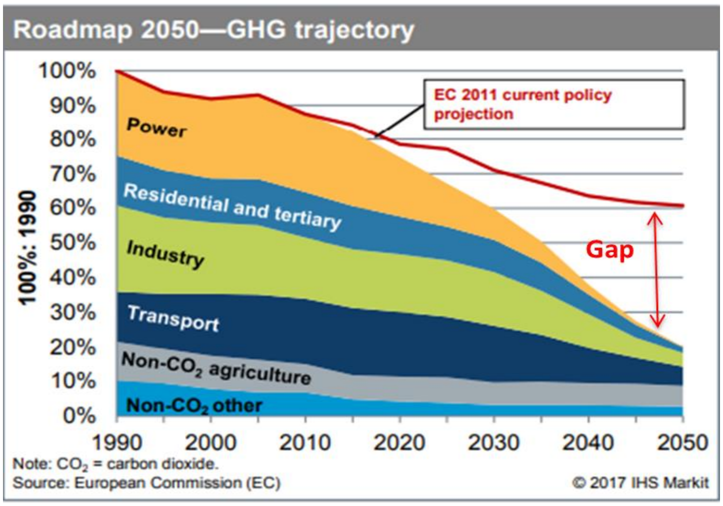

Figure 5: European Greenhouse gas reduction trajectory

Filing the Renewable Gap:
The above mentioned decarbonisation initiative, renewables' penetration as well as the shale gas constituents present large challenges to the world's energy markets, but also present an opportunity for the gas turbine market to "fill in" the gap. The gas turbine presents an advantage from a fast load availability and capability to run a wide range of fuels including hydrogen. An example can be that of a "hydrogen battery", where energy generated by gas turbines during off peak hours can be harvested by generating Hydrogen, storing the Hydrogen and releasing it in the form which can be burned in gas turbine with reduced or no carbon content.

The above market drivers/initiatives have been key in steering PSM's combustion technology development of the LEC/NexGen and FlameSheet combustion system for E and F Class heavy duty industrial gas turbines which will be discussed in the sections below.

The FlameSheet™ Combustion System

To address the need to expand a unit's operating range, PSM offers the FlameSheet™ combustion system for extended operational range. The system provides both maximum firing capability as well as minimum turndown and fuel savings at lower firing, all the while meeting existing F-class emissions limits.

As described in [6], the FlameSheet™ system is a combustor within a combustor, each of which can be operated independently of the other. The system consists of two aerodynamic stages and four fuel stages. The stages are designed for specific operational aspects such as transient loading and extended turndown operation. The two aerodynamic stages consist of a pilot along the center axis of the combustor, and a main stage surrounding the pilot. The pilot and main stages are effectively two independent combustors with their own robust flame stabilization mechanisms. This allows either combustor to be operated with the other combustor OFF, providing significant operational flexibility.

As shown in the CFD contours in Figure 6, the center core (pilot) and outer annulus main stages form two independent flame stabilization zones resulting in a "combustor within a combustor" configuration, which is key to enhancing operational flexibility.

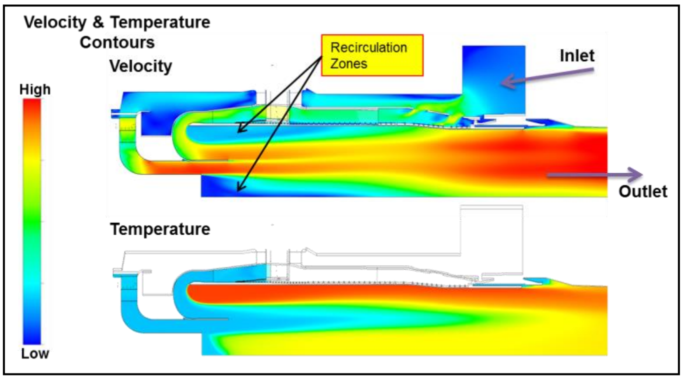

Figure 6: CFD Velocity (top) and Temperature (bottom)

As discussed in [6], fuel staging in the FlameSheet™ is simplified relative to the baseline 7FA DLN 2.6 combustion system, as shown in Figure 7. During the first mode, the combustor is ignited on a portion of the pilot flame stage and the engine is accelerated before mode 2 is reached. During mode 2 another pilot flame stage is introduced and the unit is accelerated through Full Speed No Load (FSNL) conditions and up to ~10% load. Mode 3 and mode 4 involve introducing the Main 1 and 2 stages consecutively until the lower operating load (LOL or Min Load) point is reached. Once at mode 4 (~25% load), and with all transfers completed, the engine can freely ramp up and down from the LOL point (30%-40% load, depending on emissions limit) to Baseload (100%).

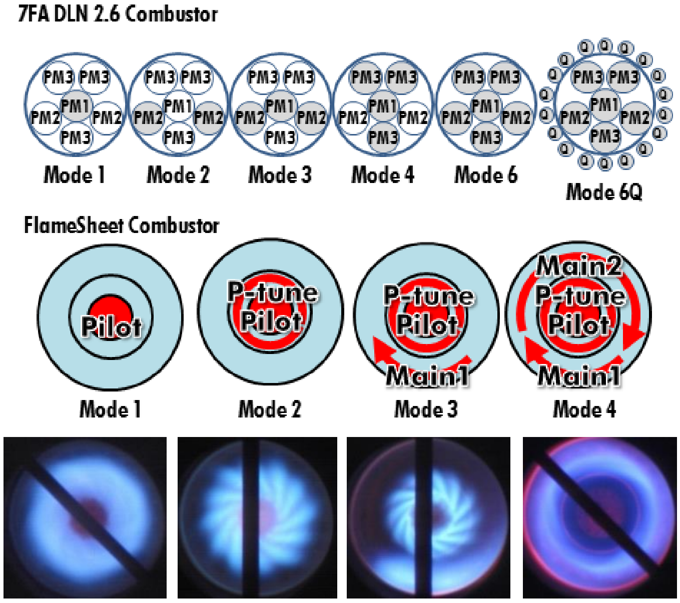

Figure 7: Mode transfer comparison: 7FA DLN 2.6 (top) vs. FlameSheet™ (middle), Flame structure for various modes from Rig Testing (bottom)

In order to permit the FlameSheet™ system to interface with multiple engine frames, various configurations exist including the 7FA Dropin, the 501F Dropin and the 7FA Low DP GTOP configurations. The modular nature of the design (Figure 8) permits the same headend components to be used in all configurations, where only the Meter Plate and Liner/Flow Sleeve is changed to permit interfacing with the unique Transition Piece (TP) and Compressor case interfaces of different units. Specifically, the Low DP version has an increased effective area design that permits a lower pressure drop through the combustion system when matched with PSM's lower pressure drop turbine hardware in the Gas Turbine Optimization Package (GTOP) to increase cycle efficiency of the unit.

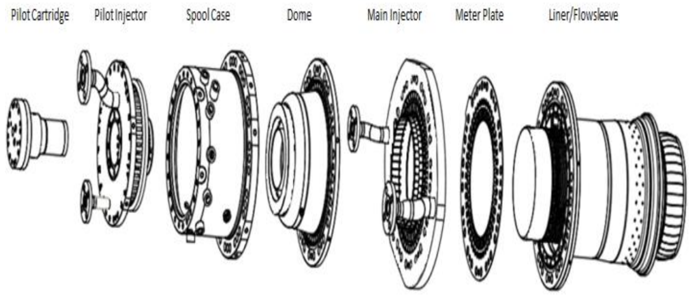

Figure 8: FlameSheet™ combustion system components

PSM 7FA Gas Turbine Optimization Package (GTOP)

The PSM 7FA GTOP package is designed to operate with lower combustion pressure drop for improved heat rate and output. The reduction in combustion section pressure drop is achieved by modification to the combustion transition piece and flow sleeve (Figure 9) to increase the overall area of the combustor, thus reducing the pressure drop across it. The transition piece cooling scheme is also modified from in impingement cooled type to effusion cooling while the flow sleeve flow area increased via increased number of holes and hole diameters. The pressure drop across the combustion system, as measured from compressor discharge total pressure to Transition Piece (TP) exit total pressure is reduced by 1.5% from the baseline combustor pressure drop for the 7FA engine. The reduction in pressure drop across the combustion system provides an immediate benefit to thermodynamic cycle efficiency and a corresponding improvement in engine heat rate. The exact heat rate improvement is engine and site specific, but PSM uses a general guidance of an improvement of approximately half of the pressure drop reduction (as percent compressor discharge pressure). So an improvement of 1.5% would equal roughly 0.8% heat rate improvement depending on site and engine conditions.

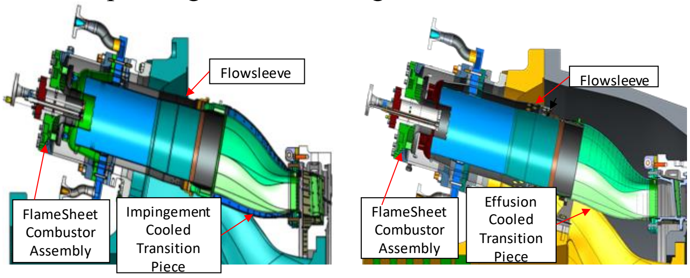

Figure 9: FlameSheet™ "Drop-in" configuration with standard pressure drop (Left) and Low ΔP FlameSheet™ system FlameSheet "GTOP" configuration with reduced Pressure Drop (Right)

In spring 2018, two Low ΔP FlameSheet™ systems were installed on 2 Frame 7FA GE F-class gas turbines, see Figure 10 below. The FlameSheet installation was coupled with PSM's Advanced HGP Turbine Performance Upgrade for improved output and heat rate.

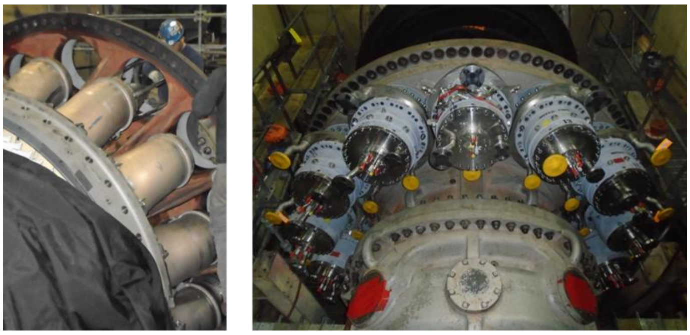

Figure 10: Low ΔP FlameSheet system with effusion cooled style Transition Piece installation on Two 7FA F-Class machines in Spring 2018

With PSM's GTOP upgrade, turbine operators are permitted to select higher levels of firing corresponding to various levels of hardware life, which can be selected and changed at any point during operation. For operators who value extended hardware life above unit output, operation at Maintenance Mode permits an increase in hardware life to extend the maintenance interval for the combustor and turbine hardware. For other operators who value load output, as well as a heat rate benefit due to the cycle efficiency improvement from higher firing temperature, operation at Peak Max is available. See [7] for more info on the FlameSheet™ GTOP details.

LEC-III Combustion System

The LEC-III technology was first incorporated into GE Frame 7E gas turbines in 1998. This can-annular, reverse-flow combustion system, shown in Figure 11, was designed to be a direct replacement into an existing gas turbine outfitted with the OEM DLN-1 system. This lean premixed system includes fuel nozzle assemblies, transition pieces, flow sleeves and combustion liners which were initially designed to achieve less than 25ppm NOx (corrected to 15% O2) at baseload conditions. To date, the PSM fleet of LEC systems has over 1,000,000 hours of operation. See Benoit et al. 7 for a full description of this system installed on multiple machines at a mature power plant.

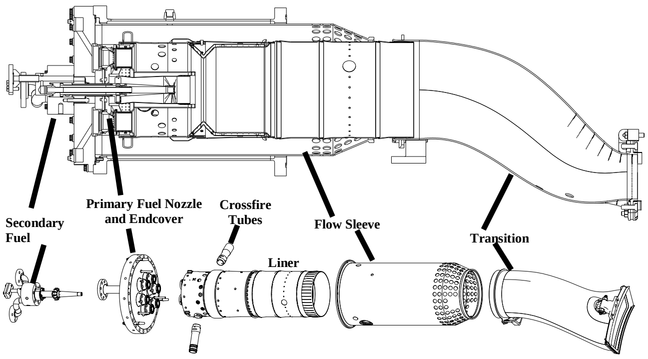

Figure 31: PSM's LEC-III® Combustion System Cross Section

There are a number of key technology advances made over the previous state of the art in the LEC-III system that enables it to perform as discussed and shown in Figure 12. The operation of this type of dual stage lean premixed combustion system is described by Davis & Black 9.

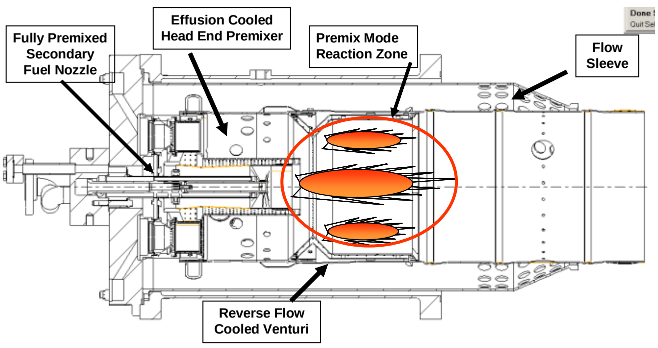

Figure 12: Combustion System Description

The key mixing features of the LEC-III include a 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.

The secondary fuel nozzle is a key contributor to the demonstrated stability of the 7E/EA OEM DLN-1 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 of premixed primary fuel. By design, this secondary reaction zone is a richer mixture, burning hotter to provide excellent combustion stability. In the conventional DLN-1 system of the 7EA, this secondary fuel flow is actually channelled 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, and it goes thru swirler vanes for final premixing prior to discharge into the reaction zone. 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. As discussed, this region has some areas of reaction temperatures above 3500F and associated NOx formation is significant. It is only a small amount of the total fuel flow, but 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 LEC-III'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 8. As a result, PSM's fully evolved, current production SFN offering is known as the "Fin Mixer" SFN, which has demonstrated in 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. Figure 14a illustrates the discussed variations of SFN fuel distribution designs, and Figure 14b shows the Fin Mixer SFN undergoing high pressure combustion tests.

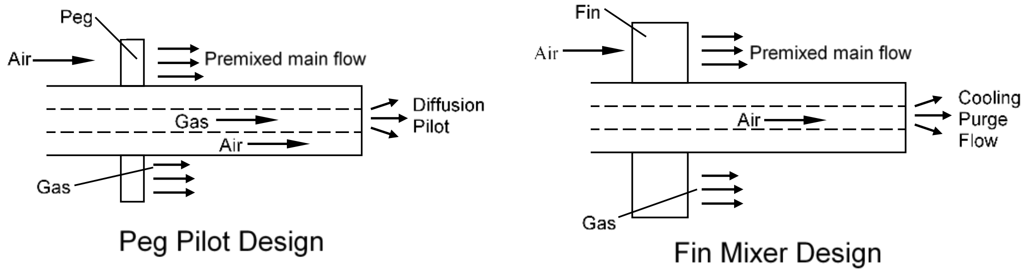

Figure 14a: Secondary Fuel Nozzle Differences

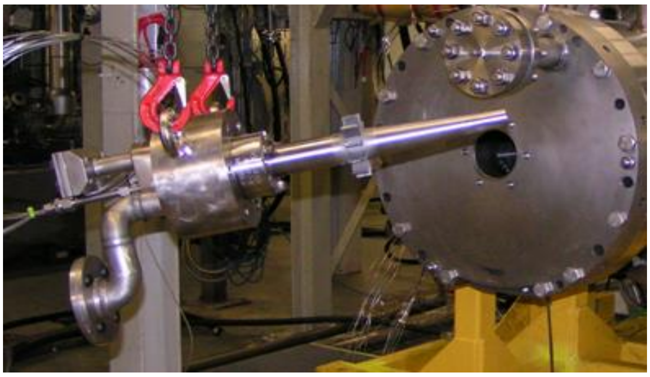

Figure 14b: Fin Mixer in High Hydrogen Test

The LECIII/NexGen system has been sold world wide on B/E class engine applications and currently at over 80 sets sold/installed in the field so far.

LEC/NexGen Rig Testing Fuel Flexibility Performance:

The results discussed in this work were obtained from engine field installations and the PSM high pressure combustion test rig. The Figure 14 below illustrates fuel constituent effects on NOx emissions. Figure 14 shows emissions from a sub 3ppm NOx PSM LEC-III™ combustion system. These systems are commercially available and operating within General Electric frame 6B, 7E and 9E machines. More than 60 machines are currently operating in the field with LEC-III™ combustion hardware. Testing was begun by correlating engine emissions with those obtained running at full scale conditions within the PSM combustion test rig. As seen below the NOx/CO relationship achieved in the field engine loosely matched the high pressure test rig results operating at the same conditions.

Testing was then repeated with increasing quantities of hydrogen. The hydrogen produced the effect of being able to run at lower flame temperature while maintaining low CO emissions and adequate stability margin. The tests demonstrated the ability of the system to operate below 2ppm NOx and 9ppm CO with the addition of hydrogen. In fact for the purposes of emissions reduction local hydrogen enriched staging could be used to operate an engine below 2ppm (see Oumejjoud et al 8). This is significant in achieving emissions typically only attainable with an SCR (selective catalytic reduction) without the associated hardware costs, ammonia emissions and debit on engine heat rate.

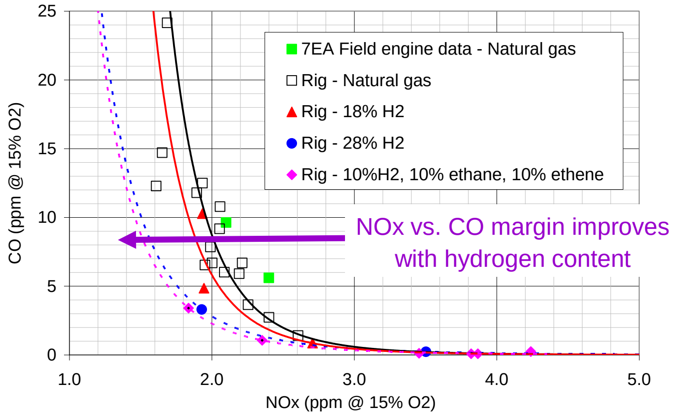

Figure 14: Emissions effect of various fuel mixtures on LEC III rig tests

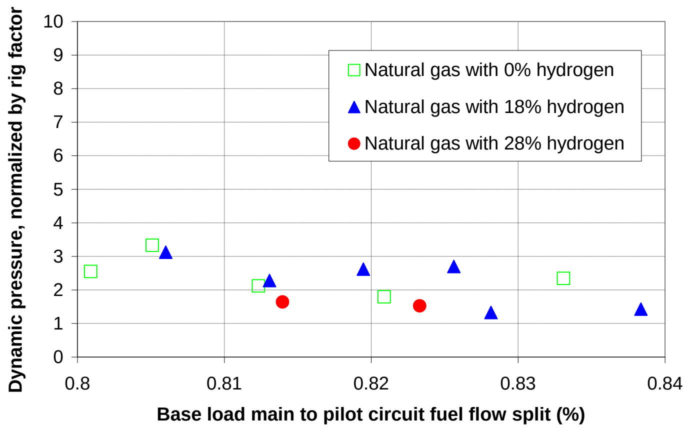

Figure 15: Combustion dynamics attenuation with hydrogen addition in full LECIII combustion system rig at full operation conditions, using nozzle shown in Figure 14.

Combustion dynamics are an important consideration in lean premixed combustion. The level of the observed combustion dynamics is can be affected by changing fuel constituents, as the fuel reactivity changes, shifting the point of heat release within the combustor. Figure 6 shows combustion dynamics plotted with increasing fuel split between the pilot and main fuel circuits. As split increases, more fuel is provided to the main circuit. The level of combustion dynamics with natural gas remains fairly constant as the split varies. Subsequent operation with increasing amounts of hydrogen showed little difference in combustion dynamics levels, with levels if anything decreasing with the addition of hydrogen.

Stability margins are affected by the flammability limits of the fuel and flame speed. Flammability is a measure of the range of fuel air ratio over which a stable flame will be maintained. Changes in the constituents may increase or decrease this range. In this way fuel constituents will affect margins for flame blow out and combustion instability.

Fuels which tend to maximize the OH- radical pool within the reaction zone will tend to maximize the flammability limits of a combustion system. Figure 16 illustrates this effect for hydrogen addition to natural gas in the premixed nozzle test rig. The average flame temperature is calculated based upon fuel constituents, fuel air ratio and operating conditions. A 111ºC improvement in flameout margin was observed with the addition of 40% by mol concentration of hydrogen, and the effect was relatively insensitive to the operating pressure of the system in question. Advantage can be taken of fuels exhibiting widened flammability envelop to reduce NOx emissions by reducing the operating temperature of the flame without compromising lean blow out margin. If no adjustment is made to the combustion system burning increased-flammability-limit fuel, the engine can be turned down to a lower minimum load without experiencing lean blow out and maintaining in-compliance CO emissions.

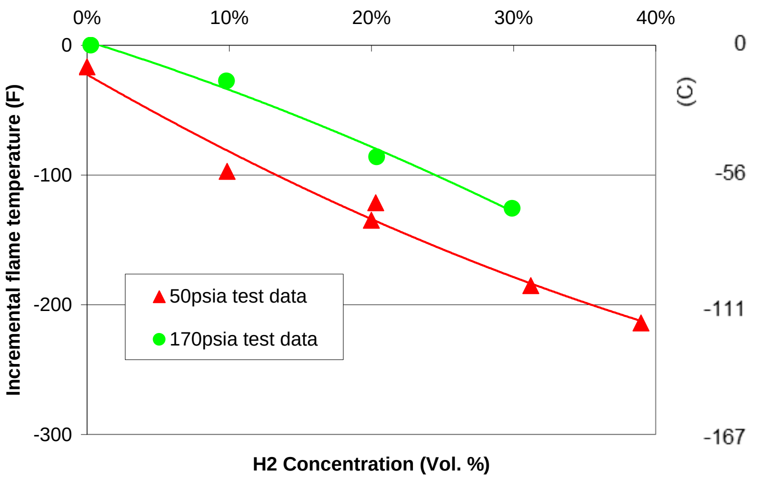

Figure 16: Flameout margin effect of increasing hydrogen content in natural gas fuel for a burner operating at two pressure conditions

LEC/NexGen Engine Fuel Flexibility Results- Hydrogen Performance:

The following section focuses on results from a 9E Engine installation where the LECIII combustor was installed to enable operation with high hydrogen content. In order to validate a new long term plant maximum of 25% hydrogen content in the fuel gas, a test program was developed with the goal of checking the combustion performance at levels beyond the expected maximum operating limit. Hydrogen targets of +5% (30% maximum) at base load and +10% (35% maximum) at 48% load were used. The level of hydrogen in the fuel gas was controlled with a gas valve mixing station, in which the percentage of hydrogen constituent in the fuel gas is measured with two redundant hydrogen analysers.

The test procedure included checking the emissions and combustion dynamics levels at varying loads and levels of hydrogen in the fuel gas. Emissions constituents measured were Nitrous oxide (NOx), carbon monoxide (CO), and oxygen percentage. Emissions data were collected via the plant continuous emissions monitoring system (CEMS). The sample probe for the CEMS is located in the stack. No exhaust conditioning systems (i.e. duct burner) were in use for the duration of the test. Combustion dynamic pressure data were collected for each chamber with a transducer mounted to the chamber casing. The location of the pressure probe is flush with the combustion liner.

Figure 17 is a plot of NOx emissions versus fuel gas hydrogen content. Two curves, one for base load and one for minimum load are shown. Base load represents maximum gas turbine load seen during typical operation. 48% load represents the lowest demand load (55MW) during automated grid control given the ambient condition of the test day. The minimum load is also slightly above the point at which the combustor will transfer out of premix combustion mode. Assuming fuel schedule is unchanged from the tested condition, the full realm of emissions data across the load range are bounded by these two curves.

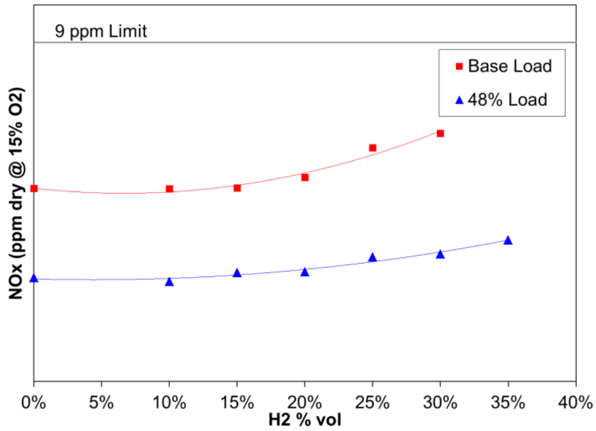

Figure 17: NOx Emissions versus fuel gas hydrogen content

As shown in Figure 17, NOx emissions are relatively unaffected by addition of hydrogen until surpassing a level of at least 15% by volume. The effect is somewhat lower at 48% load. At higher levels of hydrogen, NOx increases. Overall NOx performance with hydrogen is as expected according to prior experience [9, 10]. The maximum levels of NOx emissions seen during testing are also favourable compared to the typical limits for the combustor. Additionally, there is enough room within the limit to allow use of duct burners which add to the NOx emissions in the exhaust gas.

The result obtained with NOx emissions is to be expected due to the combination of two competing phenomena. On the one hand, hydrogen has a higher flame temperature and flame speed than methane which will move the flame upstream and change the flame geometry. The higher temperature along with greater localized fuel/air ratio serves to increase NOx formation. On the other hand, with the gas turbine operating at constant load, the higher temperature results in a reduction of total fuel flow by mass. The gas turbine control system is automatically adjusting fuel mass flow in response to the change in fuel constituent. The change in mass flow serves to reduce the effect of the higher flame temperature on NOx formation.

Figure 18 is a plot of CO emissions versus fuel gas hydrogen content. As previous, one curve is shown for each of base load and 48% load. As would be expected, CO emissions at base load are essentially zero. This is typical for most modern low emissions gas turbine combustion systems. The CO at base load is thus not affected by changes in hydrogen content. Conversely, at 48% load there is a substantial effect due to the addition of hydrogen. At a level of 10% hydrogen, the CO emissions were already in exceedance of the typical combustor limit. Elevated CO at low load is common amongst dry low NOx combustors due to the reduced localized flame temperature (high premix quality) of the combustion zone. Increasing hydrogen to 15% and higher brings the CO emissions significantly below the limit. A separate data point indicating 51% load shows the required load to reach sub 25 ppm using 0% hydrogen with the current hardware.

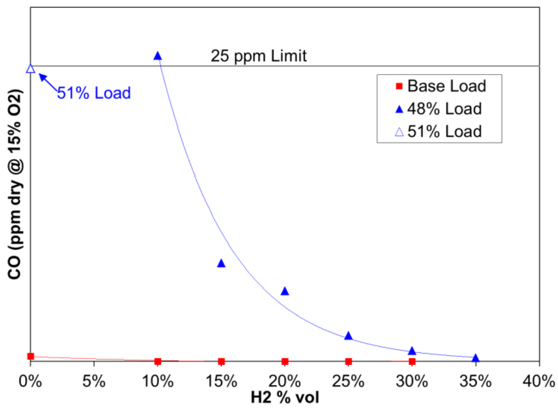

Figure 18: CO Emissions versus fuel gas hydrogen content

The result obtained with CO emissions is to be expected since with higher temperature the fuel will tend to be burned more to completion, consuming available CO. Additionally, with increased proportion of hydrogen in the supply, the availability of carbon compounds for CO formation is reduced.

Figure 5 is a plot of maximum combustion dynamic amplitude versus fuel gas hydrogen content. Again, separate curves for base load and 48% load are shown. Base load combustion dynamics were already low, and addition of hydrogen did not exacerbate the levels observed. In fact, at higher concentrations of hydrogen, a reduction of dynamic amplitudes and a widening of the tuning window were found. This result was similar to that observed during rig testing. At 48% load dynamic amplitudes were higher than base load. From a stability standpoint the combustor is certainly closer to its stability limits when running at minimum load. This is a condition that is farther off the combustor design point. Similarly at 48% load the combustion dynamics levels were lowered when hydrogen concentration exceeded 20%.

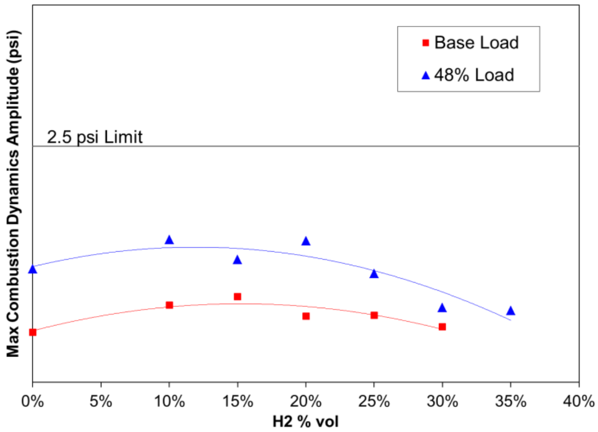

Figure 5: Maximum combustion dynamics amplitude versus fuel gas hydrogen content

The result obtained with combustion dynamics is expected to be burner specific in that the flame dynamics are moving away from hardware dynamic resonance modes. This may not be the trend if the hardware geometry is changed. Combustion dynamics play a strong role in ensuring the hardware will reach its target maintenance intervals. As shown in Figure 5, a favourable margin to the typical limit exists at both base load and 48% load.

Extended Turndown Potential

As shown in Figure 18, a strong benefit is seen with the reduction of CO when fuel gas hydrogen content is above 10% by volume. This presents an opportunity to reduce load below the level currently used for automated grid control.

Figure 2020 is a plot of CO emissions versus combustion firing temperature. The curve representing 100% natural gas shows the full range of CO emissions over the premix load range when no hydrogen is used. As shown, the gas turbine operated well below the 25ppm CO limit at 52% load. Two other data points are shown, one for 25% hydrogen and one for 35% hydrogen.

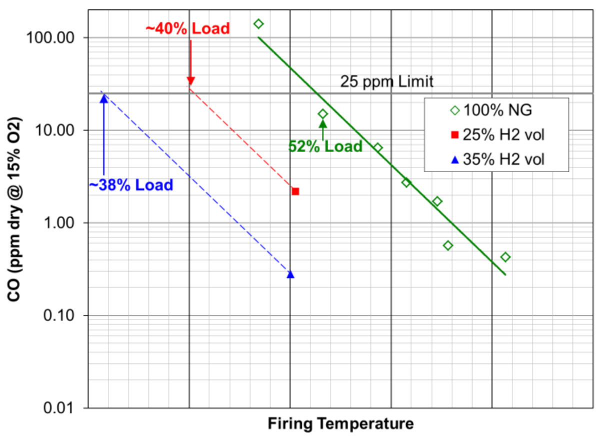

Figure 20: CO Emissions versus normalized load

As can be seen in Figure 20, the CO emissions limit is reached much sooner with 100% natural gas fuel than with 25% and 35% hydrogen fuel. The limit for CO emissions was not reached at the tested loads when operating at elevated hydrogen. From this we see a strong potential benefit to reduce load beyond the current operating minimum when using 25% hydrogen. Some limiting factors will apply, including reduction in combustion temperature with the reduction in load. Exhaust temperature is already limited to a maximum and is one of the contributing factors to the reduction in combustion temperature. This limitation is further pronounced when the engine inlet guide vanes reach the minimum angle, as any further reduction in load will reduce combustion temperature at a faster rate. In Figure 20, lines which have the same slope as the 100% NG curve are shown extending from the 25% and 35% data points up to the 25ppm limit. These lines represent an expectation for achievable turndown when operating with 25% and 35% hydrogen in the gas fuel. As is seen, the load reduces more rapidly with changes in firing temperature in this range, thus it is expected to be achievable to reduce load to approximately ~40% load when using 25% hydrogen.

LEC/NexGen Engine Installation at a Canadian Site:
In 2017, 2018, the LEC/NexGen Combustor was installed on 2 Frame 7E units at a site in western Canada, the site was seeking low NOx emissions and ability to turndown while in NOx compliance. The results below summarize the tuning performance as performed on the second unit. Similar results were obtained on the first installation in the year prior. A full tune/mapping was performed across the premixed load range from 55% to 100% load with the “as-left” tuning results as shown the figure below.

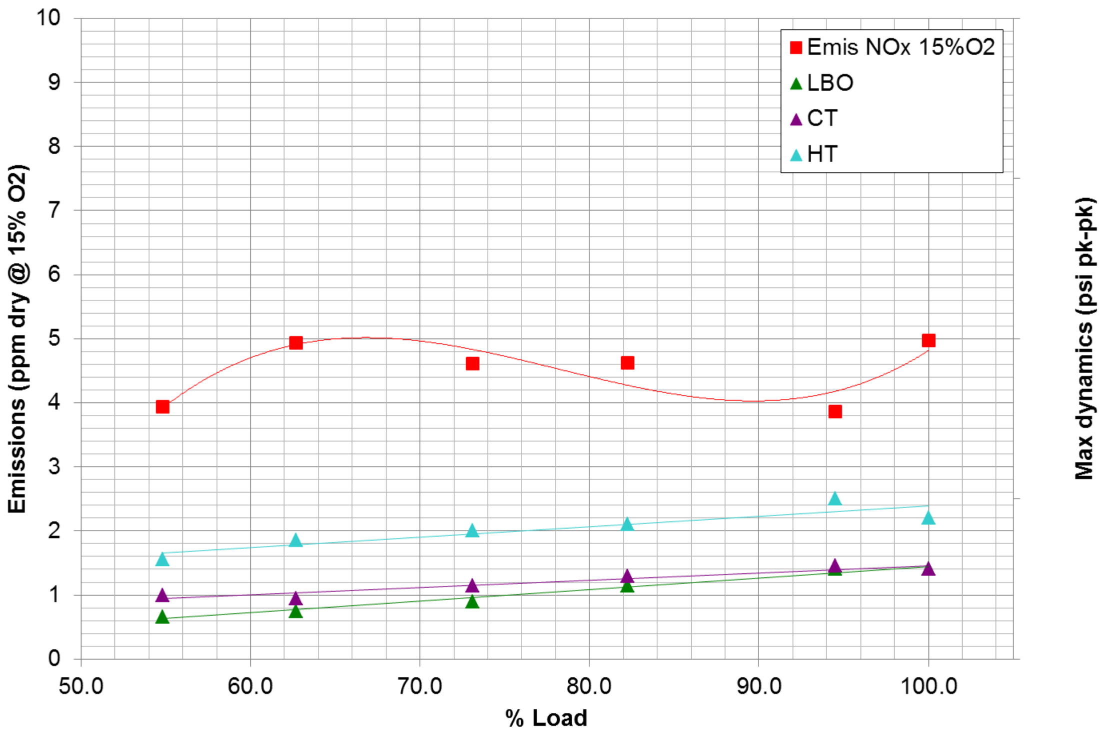

Figure 26: Premix Turndown (% load)

As shown the baseload tuning see Figure 22 below, the combustor is able to achieve <4ppm NOx operation with acceptable dynamics.

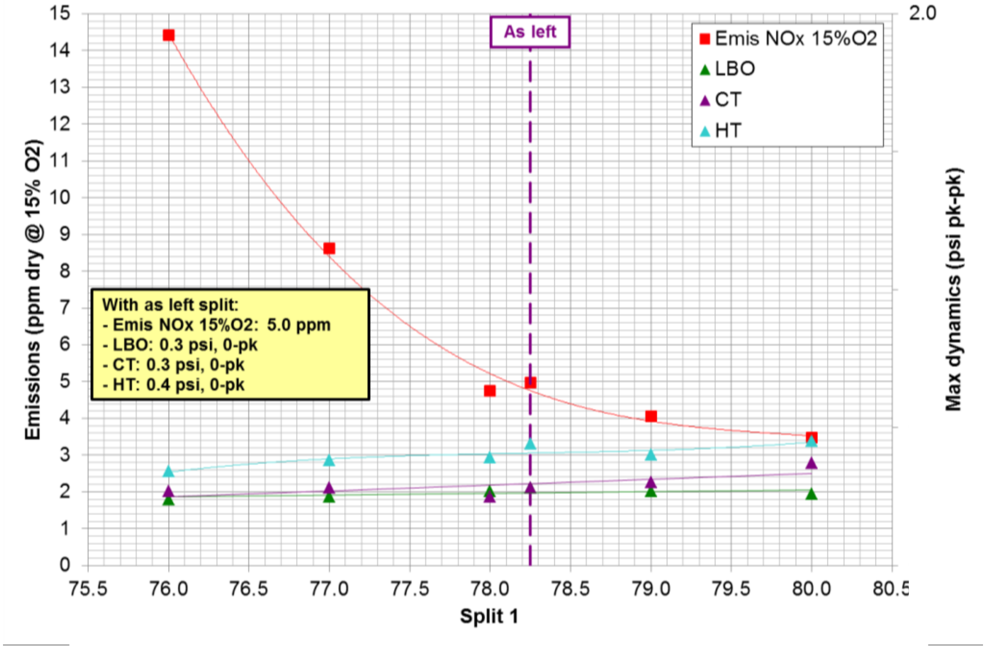

Figure 22: Baseload Tuning

Automated Tuning

Continuous automated tuning of the gas turbine combustor can be performed by an AutoTune system. The PSM AutoTune system provides the ability to continuously monitor gas turbine emissions and dynamics and perform reactive fuel split tuning adjustments to ensure these are maintained at acceptable levels. It will also apply proactive split adjustments with changes to ambient temperature, engine load, and fuel composition, based on optimal engine performance for each operating point.

Changes to gas constituents can be easily detected by the PSM AutoTune system without the use of chromatography, as explained below, and in the case of the 9E installation described in prior sections, the hydrogen content of the gas turbine's fuel gas supply will influence combustor behaviour and subsequently affect both combustion dynamics and gas turbine emissions. Furthermore, the effect of changing the hydrogen content was seen to be variable depending on the engine's operating point. As such, AutoTune measures changes to fuel composition and reacts to these accordingly.

AutoTune's effectiveness in actively tuning the unit is greatly dependent on the speed in which it can react to changes in hydrogen content. While traditional gas chromatography can accurately determine gas composition, this is generally at the expense of a long time delay to obtain measurements. The ability to proactively set fuel split adjustments for changing operating points is greatly hindered when such a time delay is experienced, causing the engine to be susceptible to high combustion dynamics or emissions permit excursions.

In order to ensure rapid response to changes in fuel, the PSM AutoTune uses a patented scheme where an internally calculated Fuel Property Parameter (FPP) determines relative variations in gas composition. The Fuel Property Parameter is a representative correlated value of the varying fuel composition, as described by Demougeot et al 6. Using fuel pressure and temperature measurements upstream of the combustor and fuel nozzle pressure drop values, a ratio of corrected pressure drop and the mass flow squared is represented as a Slope value, shown in Equation 1.

$$\mathrm{Slope}_{NG} = \frac{\Delta P_{NG_{COR}}}{\dot{m}^2{}_{NG}} \qquad (1)$$

A reference slope is determined during commissioning for a reference fuel composition – in this case, fuel consisting of Natural Gas was the reference point. Subsequently, as changes to the fuel composition occur, such as the addition of Hydrogen gas, a dynamic slope value will be compared to the reference slope value; the ratio of these is the Fuel Property Parameter, shown in Equation 2.

$$\mathrm{FPP} \equiv \frac{\mathrm{Slope}_{\mathrm{NG}}}{\mathrm{Slope}_{\mathrm{NG_{ref}}}} \qquad (2)$$

The significant advantage of this approach is the nearly instantaneous response of the Fuel Property Parameter to changes in fuel composition. This is instrumental in AutoTune's ability to record fuel split adjustments based on fuel composition, and pre-emptively apply these adjustments when returning to the point of operation.

In the 9E installation referenced project, the value of this was immediately evident when operating the unit at the plant's minimum load point. It was seen that when holding load and ambient temperature constant, varying the hydrogen composition would lead to significant changes in the engine's combustion dynamics. Due to these variations, no single Primary fuel split value would satisfy the combustion dynamics requirements throughout the entire hydrogen range.

This is demonstrated in Figure. In the 'as left' combustion baseline tuning, the 0% and 25% hydrogen data points showed the unit operating at acceptable dynamics levels. However, higher Hot Tone dynamics were seen in the 10-20% range, with a peak seen around 15%. AutoTune detected these dynamics and made the appropriate fuel split bias adjustments for the necessary fuel composition operating points, while the 0% and 25% points were not modified. These adjustments were subsequently stored, allowing for pre-emptive engine tuning based on varying fuel composition. With the AutoTune Bias adjustments proactively being integrated into the split schedule, sweeping the hydrogen content from 0-25% saw the gas turbine experiencing acceptable combustion dynamics throughout the range.

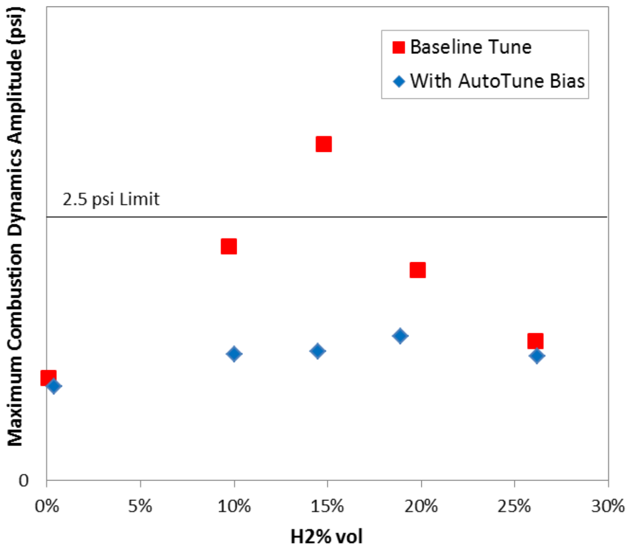

Figure 23: Combustion Dynamics versus H2% at Minimum Load for Baseline Tune and with AutoTune Bias Adjustments

Conclusions:

Based on the current global, American and Canadian energy market drivers, natural gas fired power assets are poised to benefit from available technologies to enable operational flexibility and features to improve availability, service life and overall lowered life cycle cost. The FlameSheet™ as well as the LECIII/NExGen combustion systems are easily retrofittable on existing F-Class and E-Class gas turbines and in combination with Automated tuning, can offer enhanced fuel flexibility to enable operations with shale gas, increased hydrogen gas content improved turndown and low emissions.

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