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Decarbonizing the Gas Turbine Fleet: Combustion Solutions to Meet Today and Future Energy Demands

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Abstract:

The world looks to the current installed gas turbine (GT) fleet as it is perfectly poised to meet the needs of today and tomorrow's carbon reduction goals and shifts in energy production. Regardless of the age of the unit or the marketspace, most operators need increased flexibility, whether it be operational flexibility to meet the daily changes in energy demand or fuel flexibility as the world looks to other fuels such as hydrogen to meet aggressive carbon reduction initiatives or even back up fuel to ensure grid reliability. Hydrogen, by blending with natural gas or switching to 100% hydrogen application in traditional industrial gas turbines, can be used for both energy storage and to lower emissions, as when oxidized as a fuel in a GT, there is no CO2 generated. By creating green hydrogen by renewable energy driven electrolysis, this can greatly reduce a company's carbon reduction goals. In addition, off-gases in industrial use are often flared and negatively affect CO2 output. Avoiding the need for flaring by burning these off-gases in nearby installed gas turbines can both lower natural gas costs and help meet aggressive carbon reduction plans.

A multi-platform capable combustion system designed specifically for both operational and fuel flexibility by employing a simple, two-stage radially-inflow "combustor-within-a combustor" concept that allows the staged operation of each at various load conditions, FlameSheet™ is perfectly poised as a retrofittable system to the existing installed gas turbine base. This combustor allows for a wider wobbe index as FlameSheet™ can handle a variety of fuels that pose a challenge to traditional dry low NOx combustion technology such as hydrogen without the need for additional diluents or an SCR to keep emissions low. The stability of the design also keeps the CO lower than traditional DLN style combustors as the CO "wall" is what traditionally limits low load operation. This unique combustor system can meet both the fuel flexibility demands of the near future and compete better in load following and other operational needs of today's dynamic market created by the quick onboarding of renewables. PSM will showcase our recent FlameSheet™ projects including a GE 7EA engine with up to 50% hydrogen blend by

volume being implemented in 2023. In addition to traditional hydrogen blends, PSM will also present our first FlameSheet™ retrofit burning a mix of refinery off gas (ROG) with back up liquid fuel (tri fuel) on a GE 7FA engine. In addition to FlameSheet™, PSM also has LEC-III™, our ultra-low emissions combustor designed specifically for B/E-class units which is capable of up to 50% hydrogen by volume with the addition of our latest product SFI, Sequential Fuel Injection. SFI also allows for an additional 15% swing in load for either increased output or turndown.

Introduction:

Canada as well as most countries around the globe have committed to ever evolving decarbonization goals to eliminate greenhouse gas emissions in a variety of industries. Technological growth coupled with wide sweeping infrastructure changes are key to meeting the world’s goals. Canada has had lofty goals in global carbon reduction, whereas beginning in 2013, Canada first introduced regulations on coal-fired power plants to limit greenhouse gas emissions through to the near future of 2030 where it’s been announced the end of unabated coal-fired electricity.

Historically, coal, gas, and nuclear generated energy has provided the majority of the power to the grid in North America. In recent years, Alberta is now seeing moments in electricity generation that the amount of coal generated electricity on the grid is being surpassed by the amount of both wind and now even solar generated electricity.

There is big benefit for removing carbon emitting power from the grid, but it comes at a price. Traditional baseload reliable power is being replaced by renewable power in record speed. The majority of this is either wind or solar which is variable by nature. If the wind isn’t blowing or the sun isn’t shining and there isn’t enough storage capacity in place, the grid can be in trouble.

In the US in December of 2022, winter storm Uri devastated the Midwest, hitting the PJM markets particularly hard. The extreme cold weather conditions prevented natural gas fired plants from operating. ERCOT also experienced this in 2021. Many utility, IPP, and industrial users are focused on winterization plans which include shoring up reliability with traditional base load power, such as natural gas fired power plants.

This all collectively is creating a unique need in the North American marketspace. Wind and solar being volatile by nature, but key to carbon reduction, has created grid infrastructures that are growing in daily load-swings all while reducing carbon generated electricity. The need for reliably generated electricity that can react to load swings quickly is key to continued change in the energy market. The gas turbine install base has become vastly important due to its ability to be retrofitted for technology that can reduce the prior greenhouse gas emissions of older traditional reliable electricity generation while also reacting to the swings in load and key areas of natural gas distribution disruption by operating on a variety of alternative fuels.

In addition to providing power to the grid across the globe, gas turbines are also key to driving process and providing power to industrial and oil and gas operations. For example, all major oil and gas providers and industrial operators have committed to a net zero reduction in emissions with most companies targeting 2030-2050 timelines. To achieve these goals, the gas turbine is becoming key to carbon reduction infrastructure in both power generation and industrial spaces.

Refineries and chemical producers are prime for carbon reduction initiatives when reviewing the total value chain and repurposing products and infrastructure. Hydrogen as a fuel is becoming increasingly important as hydrogen does not produce carbon as a byproduct of firing. Mixing this fuel into natural gas streams through traditionally flared gases can reduce emissions across total production operations significantly. The hydrogen economy for traditional power generation is still developing with large infrastructure needed to be put in place to create, transport, and store large grid-scale quantities. However, the current industrial and oil and gas productions across Canada, and North America as a whole, already have access to hydrogen and other gases being produced through current processes making them ripe for the next step in meeting Canada's carbon reduction goals.

With all this, PSM has been focusing intensively on the design and development and refinement of combustors for a variety of industrial gas turbine platforms in an easily retrofittable application. The primary goal of PSM's combustors are fuel flexibility, namely hydrogen blends, with sights set on 100% hydrogen operation in near term years as well as operation flexibility to meet the quickly growing grid infrastructure changes requiring reliable operation to react quickly to daily changes. Yet, hydrogen is a highly reactive fuel requiring special control and combustor design considerations to avoid flashback while maintaining NOx emissions. This has posed unique design challenges over the years.

Fuel Flexible Combustion Systems:

PSM currently has two base options of multi-platform combustor systems applicable to industrial gas turbines, 1) FlameSheet™ and 2) LEC (Low Emissions Combustor). Both combustors are retrofittable among multiple platforms with a wide range of application. FlameSheet™ has been designed and scaled to units from 1.9MW-300MW+, available on five engines today, which is quickly growing. LEC is currently fielded in seven different frame styles focused specifically on B- and E-class GE and Siemens engines. Both offer fuel and operational flexibility with low emissions without the need of diluents or SCR.

PSM has been designing and refining combustion systems to meet market demands. Requirements of design and application include dry low NOx to meet emissions demands without need of diluents or SCR, ability to blend in varying levels of hydrocarbons into natural gas streams without adverse effects such as flashback or high dynamics, real time reaction to flux in fuel stream constituencies.

1. <u>LEC-III™ Low Emission Combustor (LEC)</u>

PSM's LEC-III™ combustor is specifically designed to service the B/E-class industrial gas turbine, applicable to GE 6B, 7B, 7E/EA, 9E and Siemens 501B and 501D units as retrofittable to the OEM DLN combustion system.

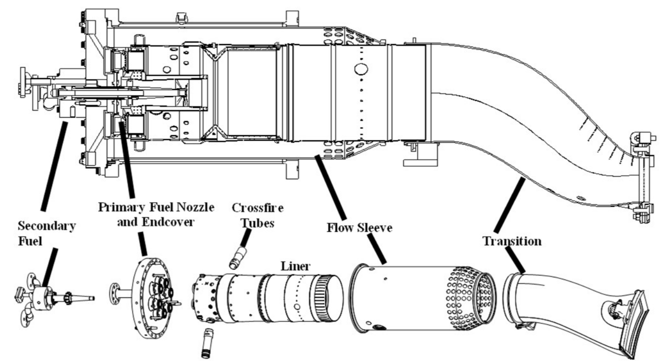

Figure 1: The LEC-III™ Combustor System by Component Illustration

The LEC-III™ is a dry low NOx system specifically targeting ultra-low emissions operation. The key to the effectiveness of this system by component is the pilotless secondary fuel nozzle "fin mixer" design, tight air flow tolerances throughout the system, effusion cooling in the upper head end of the liner, a 'reverse-flow' venturi, improved contact wear surfaces, and a robust transition piece. Specifically, regarding emissions reduction and improved fuel and air mixing, which is an enabler of hydrogen operation, there are two features are key to this system, 1) the secondary fuel nozzle, and 2) the combustion liner.

The patented Fin Mixer SFN design was developed to eliminate the nozzle tip pilot fuel, a requirement in the current OEM combustion design to control combustion dynamics. This has eliminated a small but very hot tip burning zone which is responsible for a disproportionate amount of NOx formation. Eliminating the pilot, the enabler of the OEM's traditional DLN-1 combustor, allows for better fuel and air mixing ratio without the creation of hot spots and potential reaction zone when introducing highly reactive fuels such as hydrogen.

The combustion liner uses a 'reverse flow' venturi, increased dilution air to the head-end premixer enabled by the enhanced cooling efficiency of effusion cooling.

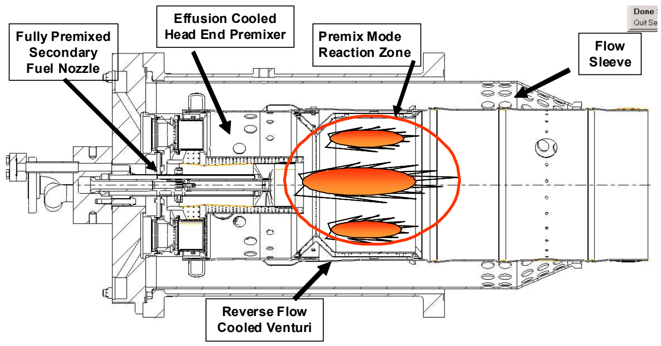

Figure 2: LEC-III™ combustion system description

Effusion cooling uses both conduction and convection and allows a more efficient use of available combustion air than the OEM configuration, which relies on a slot cooled impingement method. Because less air is used to cool the liner when compared to the OEM, more air can be mixed into the bulk fuel/air mixture via the pre-mixer dilution holes, resulting in better mixing and a leaner combustion mixture which reduces NOx generation.

An enhancement of this system, Sequential Fuel Injection (SFI), allows for splitting of the fuel and air downstream to modulate operability. This allows for swings in either output or turndown as well as an increased volume of hydrogen blending in natural gas streams after premix is achieved. This concept relies on sequential combustion, similar to flameless combustion or a reaction at low temperatures to limit NOx production and widen the operating window for reduced emissions across the load range and a variety of fuel constituents.

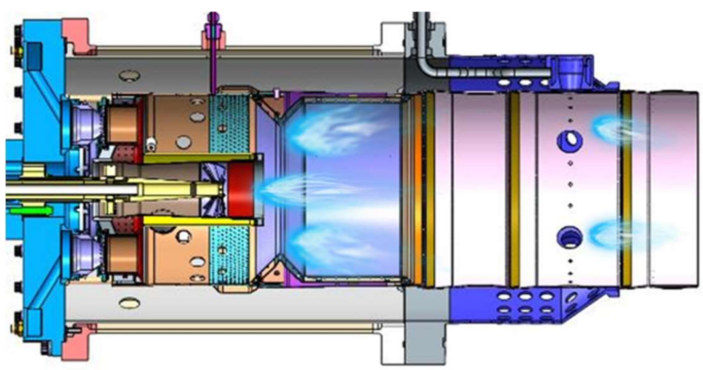

Figure 3: LEC-III™ with SFI. Illustration showing LEC-III™ cross section with SFI injectors in the aft end of the liner through the flow sleeve and lower dilution holes.

LEC-III™ Hydrogen Capability for CO2 Reduction

The LEC-III™ has demonstrated operation of up to 35% hydrogen by volume on three commercial 9E machines and continued operation with up to 30% H2 by vol since 2017 on the same units with sub 7ppm NOx emissions at baseload in dry premixed operation.

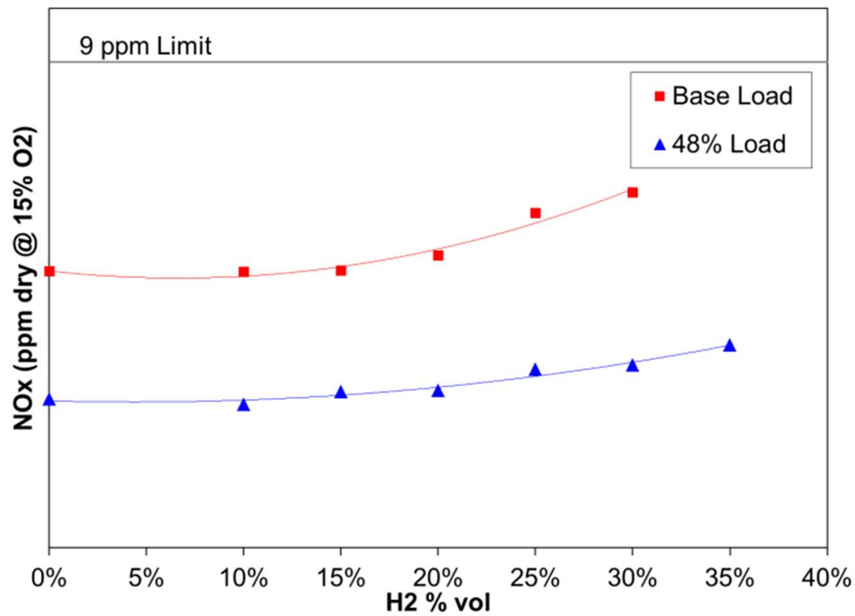

Figure 4: NOx Emissions versus fuel gas hydrogen content

The SFI (Sequential Fuel Injection) addition to the LEC-III™ combustion system enables up to an additional 10% hydrogen capability for a total of 45% hydrogen blend capability by volume with sub 9ppm NOx. The SFI additional hydrogen capability was demonstrated in high pressure combustion rig testing at full E-Class pressure capability exceeding the 45% H2 blend volume operational capability.

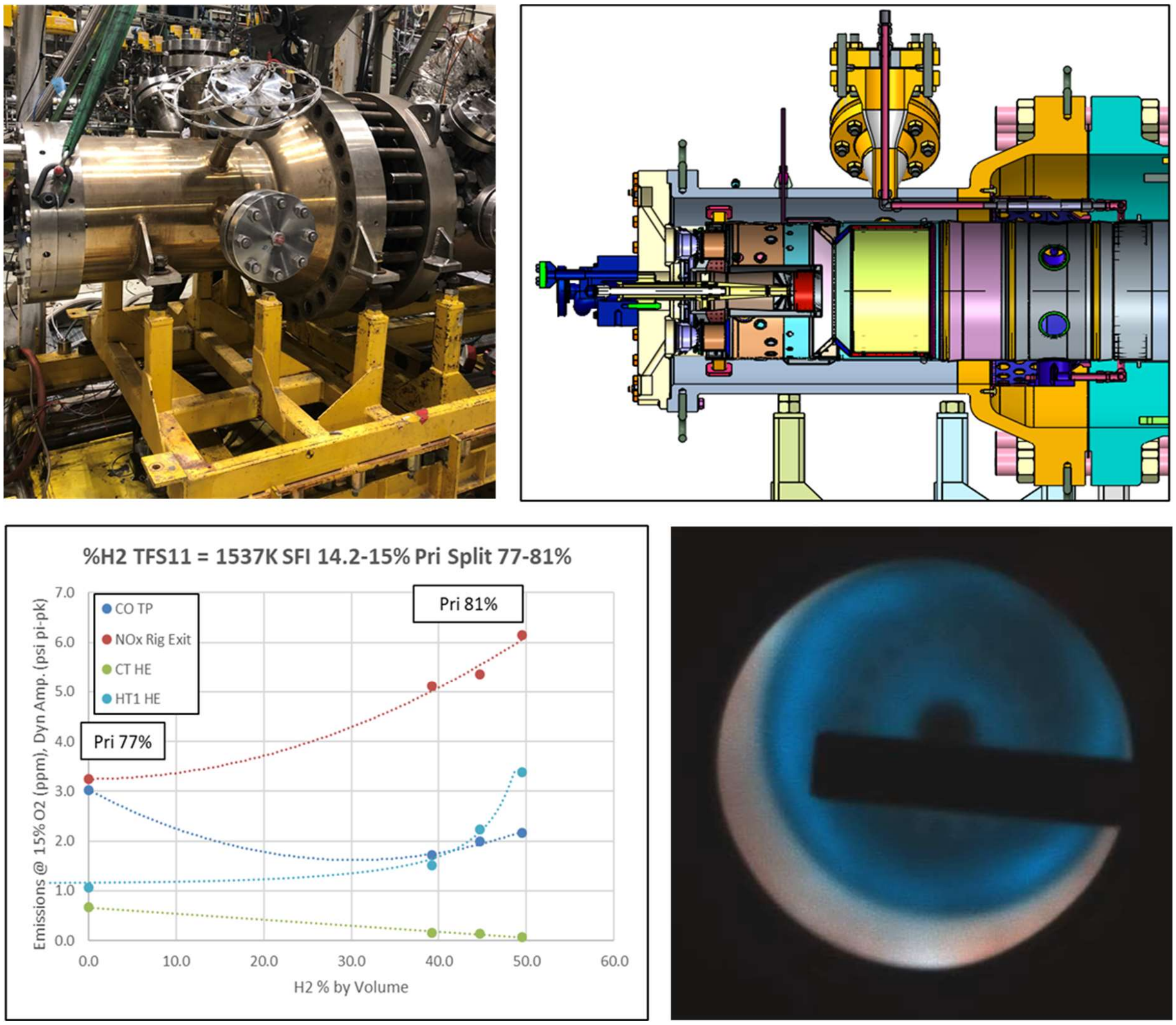

Figure 5: SFI Rig testing demonstrating > 45% H2 blend capability with single digit NOx

2. <u>FlameSheet™ Combustion System</u>

Invented at PSM in 2002, the FlameSheet™ combustion system has been designed to offer extended operational and fuel flexibility ranges to ensure maximum operating capacity and reduced fuel costs. The system utilizes a combustor within a combustor concept, 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 FlameSheet™ combustion system is designed to:

- Provide extended fuel flexibility with up to 30% modified Wobbe Index variation capability to allow simultaneous operation on natural gas, liquefied natural gas, refinery off-gas and up to 60% hydrogen blends by volume.
- Extend turndown capability to <30% load whilst maintaining emissions compliance.

- Operate below 9ppm of NOx and below 9ppm of CO across the load range, from extended turndown to baseload and overfired operating conditions.
- Allow increased firing temperature of at least 50^{o}F (28^{o}C), improving cycle performance while maintaining 9ppm NOx emissions targets
- Achieve all targets without the addition of any diluent such as water/steam/nitrogen
- Provide durability to allow continuous operation without inspection for 32,000 hours or 1250 starts
- Be easily retrofitted into existing B, E, F and Frame 5 class industrial gas turbine platforms.

An overview of the core principles of the FlameSheet™ combustor is shown in Fig. 6. The discharge plenum of the compressor feeds the pilot and main stages. Air feeding the pilot stages is flowing on the outer diameter towards the head of the combustor where it flows through the pilot fuel injector. This injector not only ensures proper mixing between the pilot air and fuel but also induces swirl in the air-fuel mixture. The swirling flow enters the reaction zone where the pilot flame is stabilized behind the bluff body that is present on the centerline. The main stage air passes between the pilot air and liner and flows parallel to the pilot air towards the head end. It passes the fuel injector that ensures an optimal fuel-air mixing profile in combination with the local velocity profile. The mixture continues towards the back end where it is turned 180 deg. At this point the flow separates from the liner and generates a strong circulation zone or trapped vortex. This zone provides a continues stabilization area for the flame resulting in an aerodynamically defined anchoring point. The fuel air mix is staged in circumferential direction to provide further operational flexibility while always ensuring a stable flame.

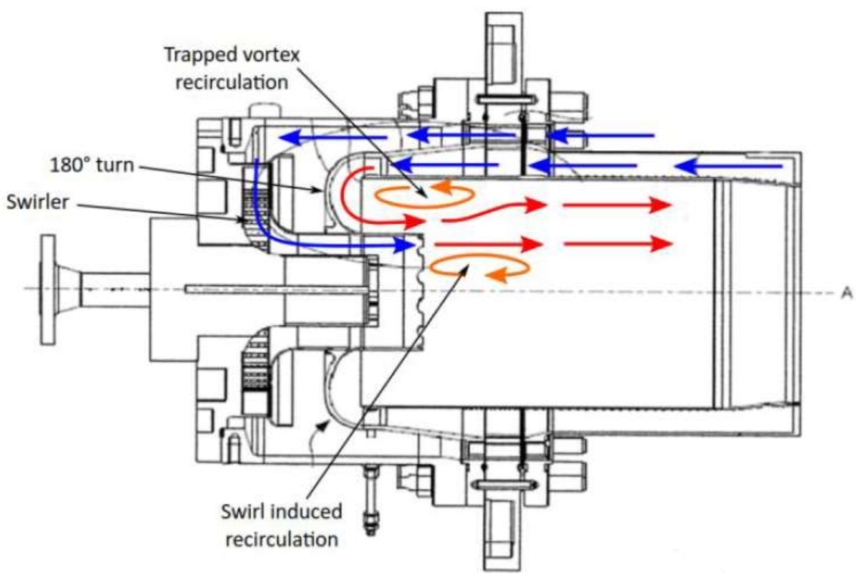

FIGURE 6: Overall flow design of the FlameSheet™ combustor.

Multi-Platform Capability:

To enable a multi-platform capable combustor adaptable to different engine frames, tolerance to varying airflow conditions, pressure drop and headend flow functions between the different combustion platforms is required. The FlameSheet™ was first fielded on the 7FA platform in 2015 but was originally designed for the 501F fleet, and the first 501F application was performed in 2020. The design was also demonstrated on the E-class 7EA platform in 2023.

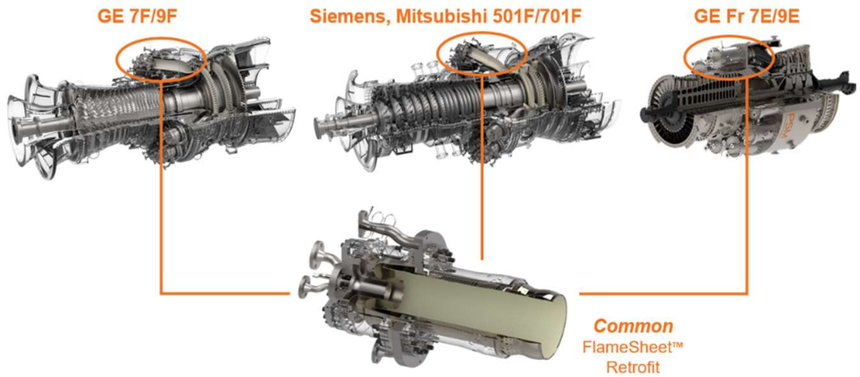

FIGURE 7: FlameSheet™ multi-platform application

The multiplatform capability was achieved by maintaining similar aerothermal characteristics across the different engine platforms essentially keeping in place the true nature of FlameSheet™ (trapped vortex technology, 4 independent pilots, etc.) See Figure below.

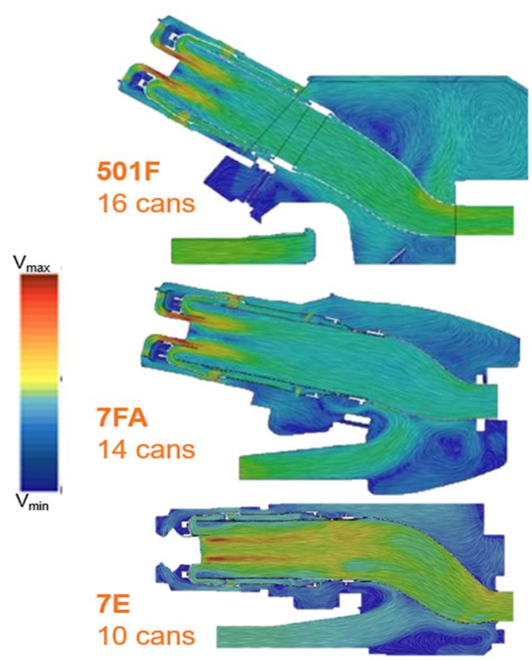

FIGURE 8: Multi-frame midframe flow velocity comparisons.

The multi-platform considerations can be summarized in the bullet points below:

Combustor airflow
- Requires tolerance/margin to flow variation.
- ~10% lower headend flow function per can between 501F vs 7/9FA - can count.
- Up to 20% lower headend flow function 7E/9E vs 7F/9F - dilution effects
- Pressure drop neutral or reduced with GTOP options for improved HR

Controls integration
- Use existing control system
- New fuel control, flame supervision & ignition logic

Fuel Delivery/Skid:
- 7F/9F→ No change 7F/9F Fuel skid, new flex Lines
- 501F→ 1 Fuel control valve trimmed, new flex Lines
- 7E/9E→ 2 Additional Fuel control valves, 1 ring manifold, new flex lines

Hardware:
- 7E/9E, 7F/9F FlameSheet™ interchangeable
- Unique Liner and Flow Sleeve required for 501F, same head end components

FlameSheet™ Scalability to GE Frames 6B and Frame 5 machines for increased Hydrogen Capability and CO2 reduction.

Leveraging advanced aerothermal analytical tools and basic fundamental scaling techniques, the FlameSheet™ combustor has been successfully scaled down to the smaller GE Frames 6B and Frame 5 class engines. HP rig testing has been performed and high hydrogen capabilities was demonstrated at full pressure and temperature.

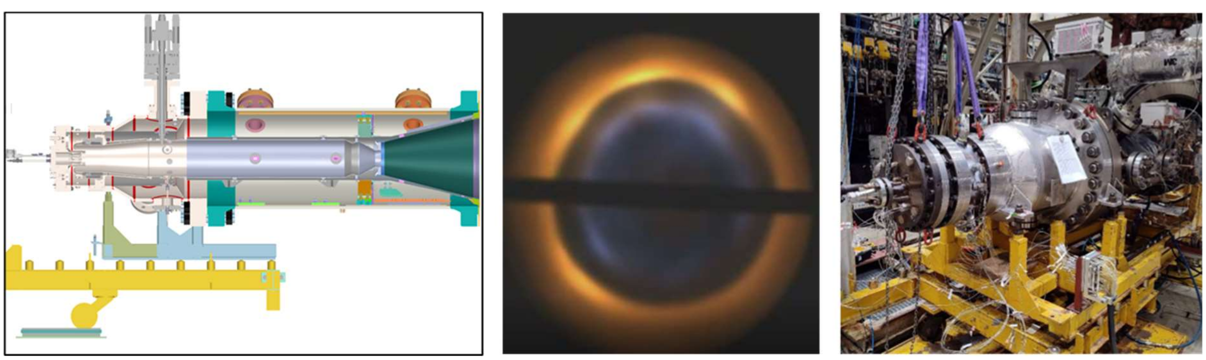

Figure 9: Frame 6B FlameSheet™ HP Rig Testing for High H2 demonstration.

Hydrogen Enablers:
Recent advancements to the FlameSheet^{TM} combustion system were made to enable the use of higher H2 concentrations as an alternative fuel and improved startup emissions performance. The was achieved through the use of a new Pilot Injector (Pilot 2.0) design

utilizing micro-mixing technology. This is considered the sixth major design evolution of FlameSheet™, in which the Pilot 2.0 can now replace the traditional radial inflow pilot injector present on all prior generations.

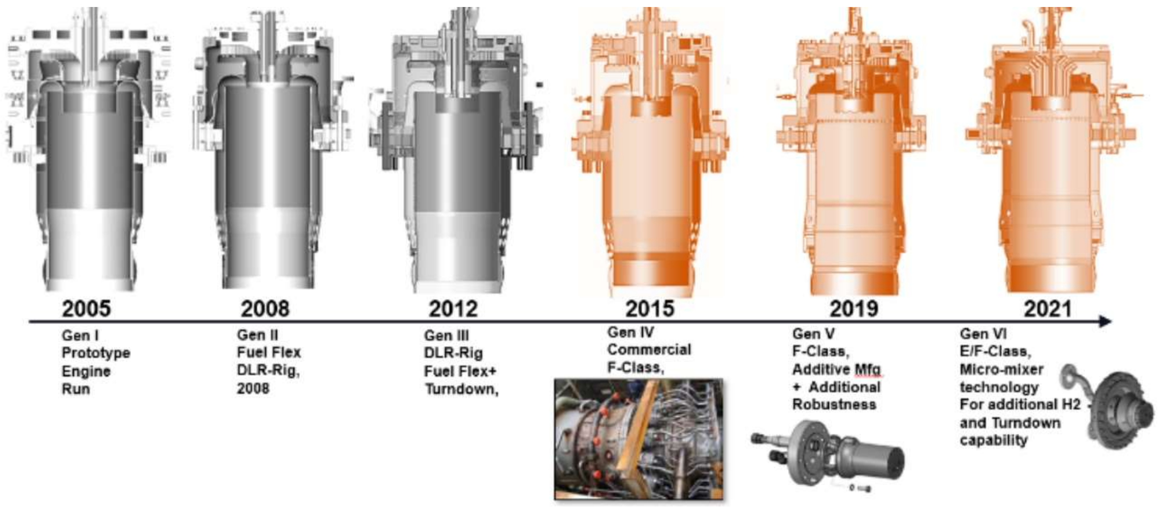

FIGURE 10: FlameSheet™ design evolution

As widely known throughout the industry, the main challenge of operating with higher H_2 concentrations is the risk of flashback. This is primarily driven by the increase of laminar flame speed, S_L. In addition to H_2 concentration, the local flame temperature, T_{FL} also affects the S_L.

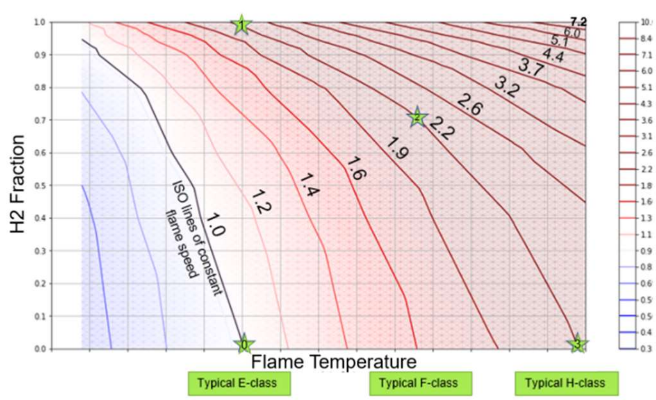

Figure 11: Influence of H_2 by volume and T_{FL} on S_L

This relationship is illustrated in the plot above (Figure), which shows the relationship between laminar flamespeed S_L as a function of H_2 by volume and flame temperature. This comparison helps demonstrate the technology challenge of premixed high hydrogen combustion. For example, a typical E-class combustion system operating at a fixed designated flame temperature T_{FL} experiences a 2.2 x increase of laminar flame speed when changing from 100% CH4 to 100% H2 (green star #0 to green star #1 on the graph). This is the equivalent of overfiring the E class combustor with CH4 to H-class temperatures (green star #3). For the same technology level (2.2x S_L capability), operating that combustor at F-class operating condition yields an H_2 = 70% by vol. capability (green star #2). By contrast, if that same technology were applied to H-class temperature conditions, the corresponding S_L isoline and T_{FL} yields H2 = 0% by vol (green star #3). The combustor designed for H-class conditions would need to be capable of SL = 8.5x more than the reference E-class system for 100% H2 concentration. The latest FlameSheet™ Gen 6, equipped with the Pilot 2.0 technology, see figure below shows a window of commercial operation up to H2 = 60% by volume.

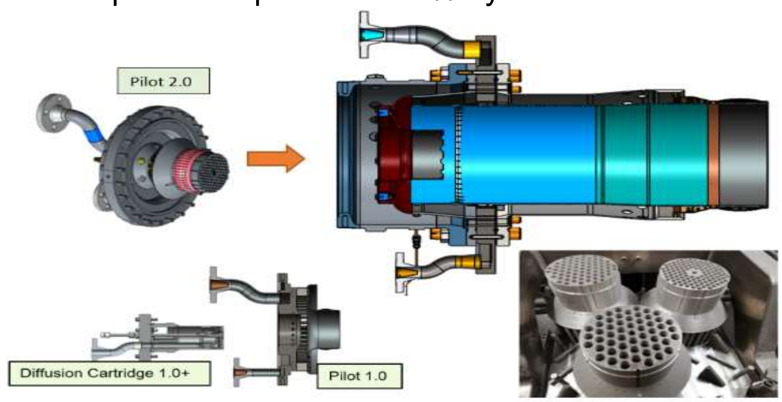

Figure 12: Pilot 2.0 retrofit overview

The Pilot 2.0 utilizes the micro-mixing technology which offers capability of up to H_2 = 60% by volume for E and F class platforms. This is mainly attributed to the improved control over the fuel air boundary layer profile and associated mixing.

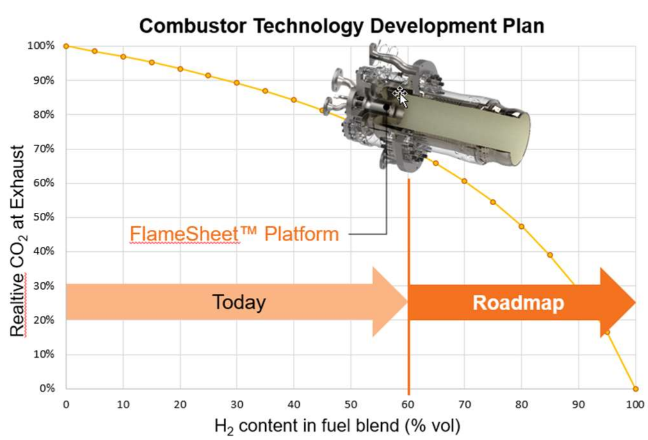

FIGURE 13: Current FlameSheet^{TM} pilot 2.0 capability

Recent Achievements in Fuel Flexibility:

1. Daesan 7EA High H2

PSM has recently demonstrated a world record hydrogen blend capability in a heavy duty low emissions industrial gas turbine application. A GE frame 7EA engine was retrofitted with the latest FlameSheet™ Gen6 technology demonstrating 60% H2 blend by volume, with stable dynamics and 6ppm NOx at baseload conditions

Figure 14: 7EA FlameSheet™ installation at Daesan Korea for high H2 application

In addition to the FlameSheet™ combustor, PSM and Thomassen, PSM's sister company strategically located in The Netherlands specifically for hydrogen combustor continued development under the Hanwha portfolio, were responsible for designing, installing and commissioning a hydrogen fuel blend skid, fuel supply skid as well a control system retrofit. Such retrofit demonstrated the ability to cut CO2 emissions by 30% while operating on the 60% H2 blend.

Figure 15: 7EA unit provided by KOWEPO Pyeongtaek site in Korea

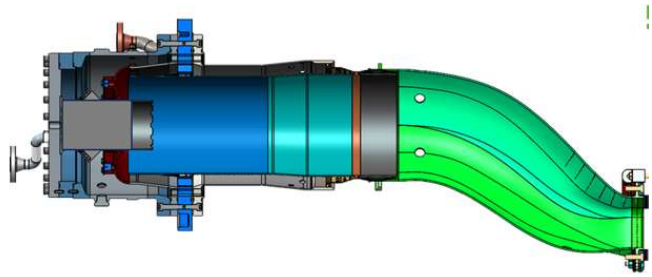

Figure 16: 7EA FlameSheet™ Design with PSM 7E Transition Piece as Installed at Daesan 7E unit ar Pyeongtaek

2. <u>Linden Cogen Refinery Off Gas (ROG) Application:</u>

PSM demonstrated successfully its first of kind refinery off gas fuel application with the ability to blend in refinery off gas (ROG) with hydrogen blends of up to 25% at part load as well as heavy hydrocarbons and other refinery off gas constituents that would otherwise be flared to the atmosphere.

The project was part of a Linden/Philips 66 initiative to reduce CO2 emissions by minimizing the use of natural gas for power and steam generation. Linden Cogen in New Jersey is a 972-MW natural gas-fueled thermal cogeneration plant featuring six gas turbines and three steam turbines, The project was implemented by retrofitting one of the site's GE Frame 7FA gas turbines with the latest FlameSheet™ combustion technology.

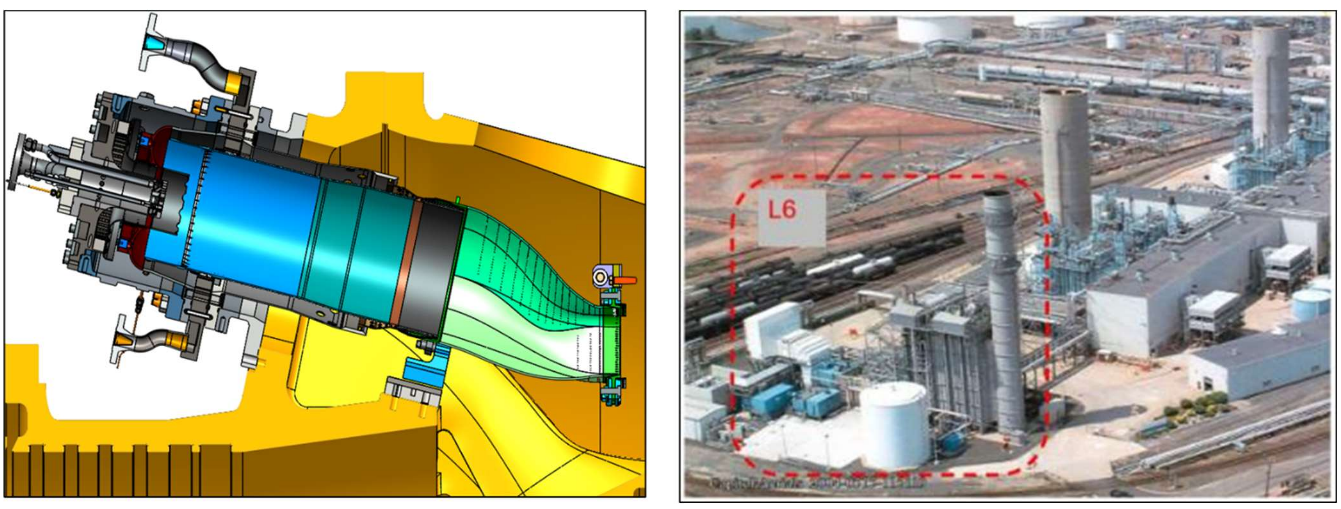

Figure 17: FlameSheet™ combustion system installation on a 7FA heavy duty gas turbine at Linden Cogen Facility in Linden NJ

Following certain modifications at the plant, including the installation of PSM's FlameSheet™ system, Linden Cogen says it is now taking refinery off gas containing hydrogen produced by the Phillips 66 Bayway Refinery, also located in Linden, and blending it with natural gas to fuel the unit 6 gas turbine. The unit consistently utilizes ROG in providing up to 67% (~14.5 lbs/sec) of its fuel supply while operating at baseload.

Such ability allows a significant offset of fuel cost and reduction of carbon dioxide emissions. For refence a 14.75 lb/s of Natural gas reduction results in ~40 lb/s of CO2 emissions.

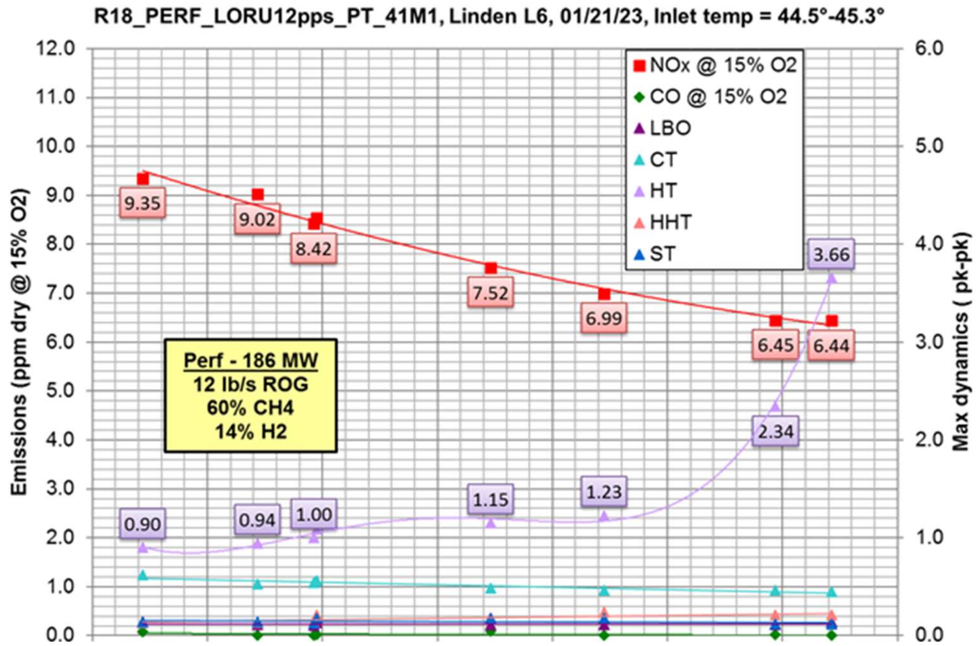

Figure 18: Sub 9ppm FlameSheet™ Operation operating with 11 lb/s of ROG at Linden

Conclusions:

Recent state of the art combustion development has been instrumental in developing solutions to reduce power plants' carbon dioxide emissions via hydrogen combustion and ability to consume refinery off gas as a source of fuel whilst reducing natural gas consumption. The FlameSheet™ and LEC-III™ combustion systems have demonstrated up to 60% hydrogen capability and offsetting over 67% of natural gas via refinery off gas consumption, thus offering viable high impact solutions to carbon reduction which have good application potential in the Canadian market.

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