Fuel Flexible Combustion Systems for High-Efficiency Utilization of Opportunity Fuels in Gas Turbines

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DISCLAIMER

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Executive Summary

The purpose of this program was to develop low-emissions, efficient fuel-flexible combustion technology which enables operation of a given gas turbine on a wider range of opportunity fuels that lie outside of current natural gas-centered fuel specifications. The program encompasses a selection of important, representative fuels of opportunity for gas turbines with widely varying fundamental properties of combustion. The research program covers conceptual and detailed combustor design, fabrication, and testing of retrofitable and/or novel fuel-flexible gas turbine combustor hardware, specifically advanced fuel nozzle technology, at full-scale gas turbine combustor conditions. This project was performed over the period of October 2008 through September 2011 under Cooperative Agreement DE-FC26-08NT05868 for the U.S. Department of Energy/National Energy Technology Laboratory (USDOE/NETL) entitled “Fuel Flexible Combustion Systems for High-Efficiency Utilization of Opportunity Fuels in Gas Turbines”.

The overall objective of this program was met with great success. GE was able to successfully demonstrate the operability of two fuel-flexible combustion nozzles over a wide range of opportunity fuels at heavy-duty gas turbine conditions while meeting emissions goals. The GE MS6000B (“6B”) gas turbine engine was chosen as the target platform for new fuel-flexible premixer development. Comprehensive conceptual design and analysis of new fuel-flexible premixing nozzles were undertaken. Gas turbine cycle models and detailed flow network models of the combustor provide the premixer conditions (temperature, pressure, pressure drops, velocities, and air flow splits) and illustrate the impact of widely varying fuel flow rates on the combustor. Detailed chemical kinetic mechanisms were employed to compare some fundamental combustion characteristics of the target fuels, including flame speeds and lean blow-out behavior. Perfectly premixed combustion experiments were conducted to provide experimental combustion data of our target fuels at gas turbine conditions. Based on an initial assessment of premixer design requirements and challenges, the most promising sub-scale premixer concepts were evaluated both experimentally and computationally. After comprehensive screening tests, two best performing concepts were scaled up for further development. High pressure single nozzle tests were performed with the scaled premixer concepts at target gas turbine conditions with opportunity fuels. Single-digit NOx emissions were demonstrated for syngas fuels. Plasma-assisted pilot technology was demonstrated to enhance ignition capability and provide additional flame stability margin to a standard premixing fuel nozzle. However, the impact of plasma on NOx emissions was observed to be unacceptable given the goals of this program and difficult to avoid.

TABLE OF CONTENTS

1 Program Objectives

The goals of this research program are aligned to support the U.S. Department of Energy objectives to 1) reduce energy intensity of U.S. industrial operations, 2) reduce overall U.S. carbon intensity, and 3) increase utilization of opportunity fuels. To do this, GE performed research and development in the area of advanced, fuel-flexible gas turbine fuel nozzles and combustion systems. The fuel-flexible combustor development program at GE targeted an optimized and validated advanced fuel-flexible nozzle design which will enable end-users to efficiently generate power and heat from industrial off-gases and gasified industrial, agricultural, or municipal waste streams, as well as blends of these opportunity fuels with readily available pipeline gases.

This program addresses the goals and objectives of the Department of Energy through the development of gas turbine combustion technology that enables efficient utilization of opportunity fuels from industrial, municipal, and agricultural waste streams to generate power and heat. The overall goal of this program is to develop low-emissions, efficient fuel-flexible combustion technology which enables operation of a given gas turbine on a range of opportunity fuels that lie outside of current natural gas-centered fuel specifications. The program encompasses a selection of important, representative fuels of opportunity for gas turbines with widely varying fundamental properties of combustion. The research program covers conceptual and detailed combustor design, fabrication, and testing of retrofitable and/or novel fuel-flexible gas turbine combustor hardware, specifically advanced fuel nozzle technology.

<u>The objectives of the program are as follows:</u>

- Define and evaluate fuel-flexible combustor nozzle concepts for utilization with a wide range of opportunity fuels
- Development and validation of analytical tools that will be useful in this program and future applications for evaluation of fuel-flexible combustion concepts
- Experimental evaluation of fuel-flexible nozzle concepts and validation of model predictions
- Design, build and test of down-selected nozzle hardware at full gas turbine combustion conditions using target opportunity fuel blends

The final commercial goal of this program is a validated fuel nozzle technology and design tools for a fuel-flexible, retrofitable, combustion system for a GE gas turbine.

A primary goal of the Department of Energy is to reduce the energy and carbon intensity of industrial processes. This research and development program addresses this goal by developing innovative combustion technologies that when deployed commercially, will enable US industry to increase utilization of opportunity fuels in efficient and clean-burning power generation gas turbines, and expand the installation of combined heat and power (CHP) applications. For large electric power generation, natural gas-fired, combined cycle power plants are currently the preferred technology. They are cost-effective (operating with nearly 60% combined cycle efficiency) and environmentally friendly (routinely producing less than 0.08lb NOx/million Btu, or less than 25 ppm NOx on a dry, 15% O2 basis). This technology has also proven to be extremely reliable in operation on natural gas.

The scope of this program is a phased development of fuel-flexible combustion systems that enable the use of a range of fuels of opportunity in gas turbines. The fuel inputs to this machine might be any of a variety of gaseous or gasified fuel streams, derived from sources including biomass and agricultural waste, municipal waste, and industrial waste and byproducts. Fuel-flexible combustion capability is a key enabling technology for meeting requirements of utilization of fuels of opportunity in gas turbines while simultaneously achieving the low emissions targets of 0.05lb NOx/106 Btu by 2010, and eventually 0.01lb NOx/ 106 Btu. Successful development of low-emissions combustors for operation on opportunity fuels will be accomplished by leveraging lessons learned from the development of dry low-NOx (DLN) combustion systems operating on natural gas and from the development of low-NOx IGCC syngas combustors. With current technology, if the gas fuels lower heating value (LHV) changes by more than a few percent, hardware modifications are typically required for acceptable operation. This increases cost and reduces availability for the machine. Fuel-flexible combustion technology will overcome the inflexibility of current premixed gas turbine combustion systems that are designed for specific fuel compositions and can typically control no more than two specific fuel composition streams.

2 Introduction

The primary goal of this program is demonstration of new fuel nozzle technology concepts for gas turbine operation on a wide spectrum of opportunity fuels and/or fuel blends. Successful technology concepts will be developed and tested through full pressure, full temperature single nozzle component combustion testing at GE Global Research. One aspect of the main objective is to develop fuel flexible combustion technologies that maximize the interchangeability of fuels in a given gas turbine configuration. A second aspect of the main objective is to develop new fuel nozzle technology that enables gas turbine operation on ultra-low-Btu fuel streams such as very weak natural gas, highly diluted industrial process gases, or gasified waste streams that are out of the capability range of current product offerings for premixed and diffusion flame combustors — particularly in the small heavy duty and aeroderivative gas turbine machines. In Phase I, based on the market assessment, a selection of target fuels or fuel blends and a GE gas turbine cycle was chosen as the test vehicle for the technological development, thus defining the gas turbine combustion system inlet pressure and temperature as well as the turbine firing temperature. New nozzle concepts were defined, evaluated and compared using analytical design tools, and down-selected. Potential concepts at this stage included advanced fuel-flexible diffusion, partially premixed, or premixed fuel nozzles and advanced flame stabilization technology for ultra-low Btu fuels - specifically plasma-assisted combustion. Initial bench-scale combustion experiments of the advanced fuel nozzle concepts were conducted in parallel with advanced development of plasma enhancement technology. Based on the experimental work in this stage, the predictive models were validated and the concepts were further down-selected for testing in the next phase. Phase II was the final build and test of the successful nozzle concepts in GE Global Research's high pressure combustion test facilities at full gas turbine combustion temperature and pressure conditions.

Conventionally, the majority of power generation gas turbines are operated on natural gas; it has become a major energy source for the US due to its availability, low cost, simplicity, and reliability of service. However, the combination of our heavy reliance upon this source coupled with recent volatility in supply and pricing is the driver to seek alternative fuels. There is a wide range of opportunity fuels that can be utilized to offset natural gas usage. The focus of this program is on portions of this fuel space that may not currently be served well by high efficiency gas turbines, and those that would benefit from fuel-flexible low-emissions combustion technology advancement.

There are many competing design challenges for a gas turbine combustion system: high efficiency, low CO emissions, low NOx emissions, combustor dynamic pressures, and turndown. Combustor design requires balancing competing requirements to have a successful product. Satisfying all constraints is becoming increasingly difficult due to conflicting demands for lower emissions, longer life, lower cost, and higher efficiency (higher firing temperature). The requirement of fuel flexibility is an additional constraint which current design approaches do not satisfy.

Premixed flames are the basis for modern dry low NOx (DLN) combustion systems, as the flame is more compact, produces less soot and unburned hydrocarbons, and, because it burns cooler than the diffusion flame, creates less NOx than diffusion flames. However, premixed flames bring with them the challenges of flame stability and decreased turndown capability. Both the fuel composition and lower heating value affect the flame speed and thus the stability margin for premixed operation. Hydrogen has a notoriously high flame speed, nearly an order of magnitude greater than that of methane, thus requiring a different design approach for fuel nozzles compared to natural gas premixers. At the opposite end, fuels with high CO and multiple inerts, such as the Blast Furnace Gas (BFG) fuels, may pose flame stability problems and the combustor design needs to change appropriately. Low heating-value fuels create a challenge for premixed flame operation due to the significant change in the fuel/air mass flow ratios. The limit on F- class combustors without natural gas augmentation is reached with approximately 100 Btu/scf fuel demanding a fuel-air ratio of nearly unity by mass, much higher than the fuel/air ratio of 0.04 more typical of higher Btu fuels. To maintain premixed operation over a range of LHV, some flexibility in the fuel or air staging, novel advanced fluidic mixers or non-conventional stabilization mechanisms need to be introduced.

NOx production is due to a number of factors, including the equivalence ratio, the combustion temperature, the residence time, and the amount of nitrogen chemically bound in the fuel. As the composition and LHV of the fuel change, the excess oxygen, excess nitrogen, and peak combustion temperature will also change. The effect on NOx emissions for both turbulent premixed- and diffusion-based combustion is such that if a premixed combustor can be designed to handle this wide variety of fuels, single digit ppm NOx is clearly achievable. This is due to the combined effect of the reduced combustion temperature typical of premixed performance and the lack of excess oxygen in the product gases. It is also clear that the diffusion flame produces large amounts of thermal NOx only when the LHV of the fuel is high, because of the strong dependence on the peak flame temperature.

The stability margin of premixed combustors is another difficult performance parameter to predict for lean premixed systems. This margin is the limit of operation for the burner in terms of flashback, liftoff, extinction, and the magnitude of pressure oscillations. Even within the range where the flame will not lift off or flashback, small changes in the operating conditions, the flow streams, or the combustor hardware can give rise to undesirable pressure oscillations. These thermoacoustic oscillations are induced by either instability in the flame front or a coupling of pressure perturbations into the fuel stream. To discourage fuel-system coupling, various orifices are placed in the fuel injection system to induce a pressure drop. Firing a gas turbine on fuels with a varying LHV or composition affects this pressure drop as characterized by the Modified Wobbe Index, expressed as:

$$MWI = \frac{LHV}{\sqrt{S.G. \times T_{fuel}}} \quad (1)$$

where S.G. is the specific gravity of the fuel and T_{fuel} is the fuel temperature in Rankine. Because of the influence of this index on flame stability, current commercial low emission combustor design practice limits variation of this parameter for any particular fielded unit at +/-5%. As might be expected, this limit reduces system flexibility and leads to design on a site-by-site basis, increasing the cost of the combustor. If there are changes to the fuel compositions leading to Wobbe number change greater than 5%, then modified combustor hardware may be required. There are additional factors that are not captured by the Wobbe index characterization, including the flame speed of the fuels and their potential for soot formation. Designing low emission combustion systems that can handle a wide range of fuels involves consideration of all of these factors.

3 Fuels of Opportunity and Their Application to Gas Turbines

3.1 Fuel Application Groupings

America's opportunity fuel space can be grouped in different ways in order to characterize their application requirements for gas turbines. First, we can consider which fuels are essentially "ready for gas turbine use" vs. those which require a conversion technology, and therefore added infrastructure. Gas-phase fuel stocks include fuels from natural gas or oil field processing operations ("weak" or "rich" natural gas), blast furnace gas (BFG) and coke oven gas (COG) from steel mill operations, landfill gas (LFG), and off-gases from petrochemical refining operations. On the other hand, all biomass sources, black liquor from paper pulping operations, petroleum coke, and municipal solid waste require gasification from their solid or liquid-solid forms. Municipal, industrial, or agricultural organic liquid waste streams can be converted to a methane/carbon dioxide mixture via anaerobic digesters.

A second way to classify the opportunity fuels is by the fuel source in relation to the utilization of the fuel. Several fuels that are products of industrial operations will likely be utilized onsite in order to produce electricity and/or heat for the industrial operation, decreasing the requirement to purchase standard fossil fuels or electricity to power its operation. Excess onsite electrical power production may even be sold back onto the grid. These operations are in a situation where availability of the fuel and requirement for power or heat generation go hand-in-hand. Examples of this include black liquor, petroleum coke, gas/oil field processing off-gases, BFG and COG, industrial waste digester gas (and perhaps municipal waste digester gas), refinery off-gases, and some biomass in the form of residues and slash from forest product industries. Because the opportunity fuel source is tied to the operation, the risk of fuel stock availability is significantly decreased for these applications. The remaining fuel sources, on the other hand, are not as closely tied to their consumption: agricultural biomass, municipal solid waste, and landfill gas. Petroleum coke, being produced in significant quantities and utilized in a manner similar to coal (Booz-Allen-Hamilton, 2007), may also fall into the latter category if it is transported and used away from the refinery source. In these cases, installation of new fuel-flexible gas turbine hardware may hinge on the capability to operate on standard fuels should the opportunity fuel supply be interrupted.

A third way to consider the use of these fuels is whether their improved utilization will require an upgrade or retrofit of an existing gas turbine vs. the installation of a new gas turbine, combined cycle power plant, or integrated gasification-combined cycle plant (IGCC). Several industrial users currently employ gas turbines for onsite power, and advanced fuel flexible technology will simply enable these users to decrease their use of purchased natural gas or fuel oil in favor of available opportunity fuel streams. Examples are refinery operations, gas/oil field operations, and energy-intensive industries that currently co-generate power and sometimes heat or steam for their own operations. For the utilization of solid- or liquid-phase opportunity fuel stocks, gasification or digestion hardware along with fuel clean up and conditioning will be additional capital requirements in addition to the gas turbine upgrades or installation of new turbines.

Finally, the applications will typically fall into two categories – those which will require co-firing or blending of standard fuels simply because of the limited quantity of opportunity fuel, vs. applications where the full gas turbine fuel requirement can be satisfied with an available opportunity fuel source. This situation is likely to vary widely over almost all of the fuel source categories – making the development of a broadly fuel-flexible combustion system even more important for implementation across the industrial spectrum.

3.2 Opportunity Fuels Landscape

A survey of opportunity fuels in the U.S. was conducted, based on publicly and privately available data and typical compositions of gaseous and gasified fuels were assembled to define the fuel space (see Table 1).

Table 1: Opportunity fuels and their characteristics

Fuel source	Fuel composition	LHV range [Btu/scf]	MWI range @ 100F	Max H2	Max C2	Max C3	Max C4	Max inert (CO2 or N2)	Min CH4
	NG/N2 (N2~60%)	365	17.2		0	0	0	60	40
	NG/CO2 (CO2~60%)	365	14.5		0	0	0	60	40
	NG/C2 (C2~40%)	1196	58.5		40	0	0	0	60
Weak NG field	NG/C2~33%max/C3~15%max/C4~10%max	1390	62.5	0	33	15	10	0	67
	High HC's	1024-2197	54-77						
	H2/CH4	619	45						
Rich refinery/	CO/CH4	729	37						
petrochemical	N2/CO2/CH4	638	29-33						
offgases	Inert/H2 or Inert/CO	260	12.9	46	38	19	18	31	10
	>97% CH4 (typically injected in NG pipeline)	950							
Coal mine methane	49-89% CH4; 4-42% N2/CO2; 0-26% C2/C3	350-1440	?	0	16	11	2	42	49
	CH4/CO2 (CO2~40%)	547	23.8						
Landfill gas	CH4/CO2 (CO2~60%)	365	14.5	0	0	0	0	60	40
	Air-blown (**N2**, CO, CO2, H2, CH4)	140-180	6.2-8.2	16.5	1.5			66	3.9
	O2-blown (CO2, H2, CO, CH4)	297-328	13.9-14.2	32.8	4.4			46.8	17
Gasified biomass	Indirect (steam) (CO, H2, CH4, CO2, C2+)	433-548	21-25	22.5	7.2	0	0	12	14
	Press. O2-blown (H2, CO, CO2, CH4)	173	13	41				17	2.1
Gasified black liquor	Indirect (steam) (H2, CO, CO2, CH4)	278	17.5	62	0	0	0	10.5	3.5
Gasified petcoke	O2-blown (CO, H2, CO2, N2)	248	12	32	0	0	0	18	0.1
Gasified MSW	O2-plasma (CO,H2,H2O,CO2,N2)	90-240	3.7-12.9	38.1	0	0	0	69.1	0
Digester gases	CH4/CO2/N2 (60-70% CH4 / 30-40% CO2 / N2)	542-659	23.7-31	0	0	0	0	40	59.5
	BFG: N2/CO/CO2/H2 = 55/24/18/3%	85	3.5	3				73	0
BFG/COG	COG: H2/CH4/CO/N2/CO2=57/25/8/7/3%	410	28.5	57	0	0	0	10	25

The fuel space, highlighted in Figure 1, is broken up into several sub-groups: gasified fuels (syngas), characterized by high H_2 and CO content; high-inert natural gases, including high N_2 and CO_2 content; refinery off-gases, characterized by high hydrocarbon and/or high H_2 content; and steel mill gases, specifically blast furnace gas and coke oven gas. Based on the broad spectrum of low-Btu fuel sources and the high potential for displacement of natural gas in the

U.S. from these opportunity fuels, this program was focused primarily on the fuels in the low heating value end of the fuel space. Secondarily, refinery or petrochemical off-gas fuels are an important group of fuels that were addressed as well.

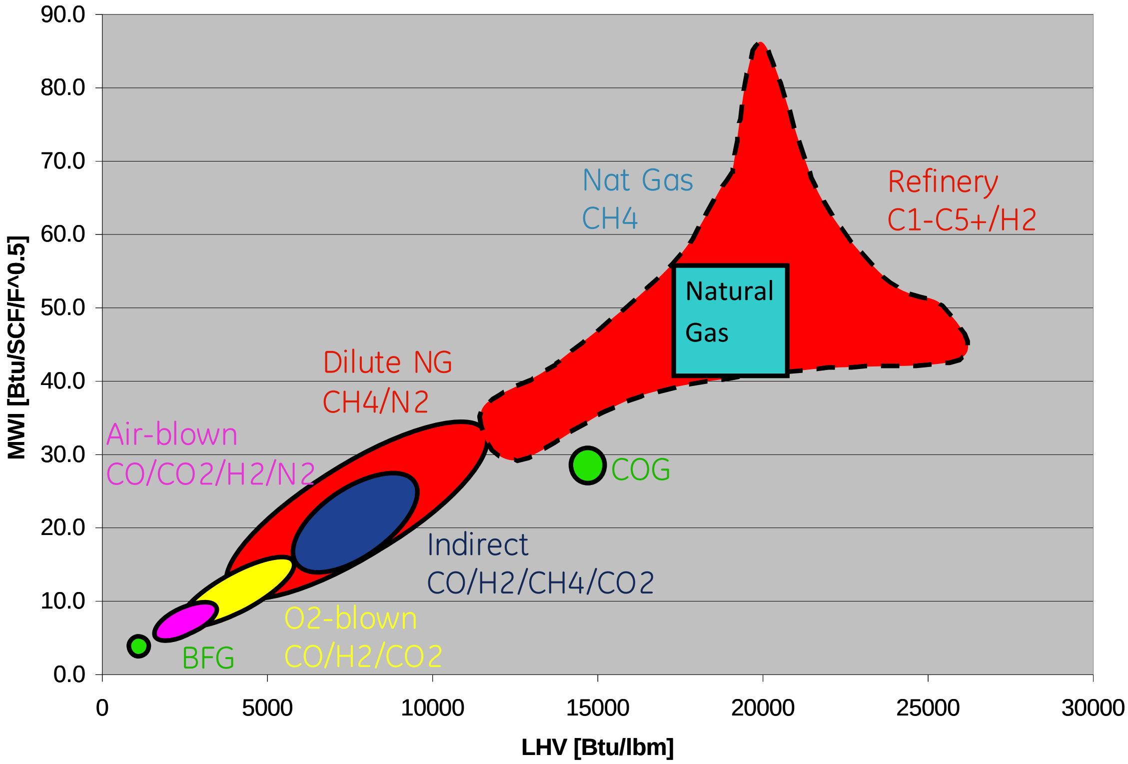

Figure 1: Opportunity fuel map - general groupings

3.3 Definition of Fuel Flexibility

Fuel flexibility for gas turbines can be defined in two ways. One way to define the fuel flexibility of a given combustion system is by the total range of fuels over which the system can be optimized to operate, given slight modifications in hardware or control system. New gas turbines today are typically designed, or at minimum "tuned," for optimum performance on a specific fuel composition provided by the customer. The range of fuel compositions in which a machine can be optimized could be described as Range A, depicted in Figure **2**.

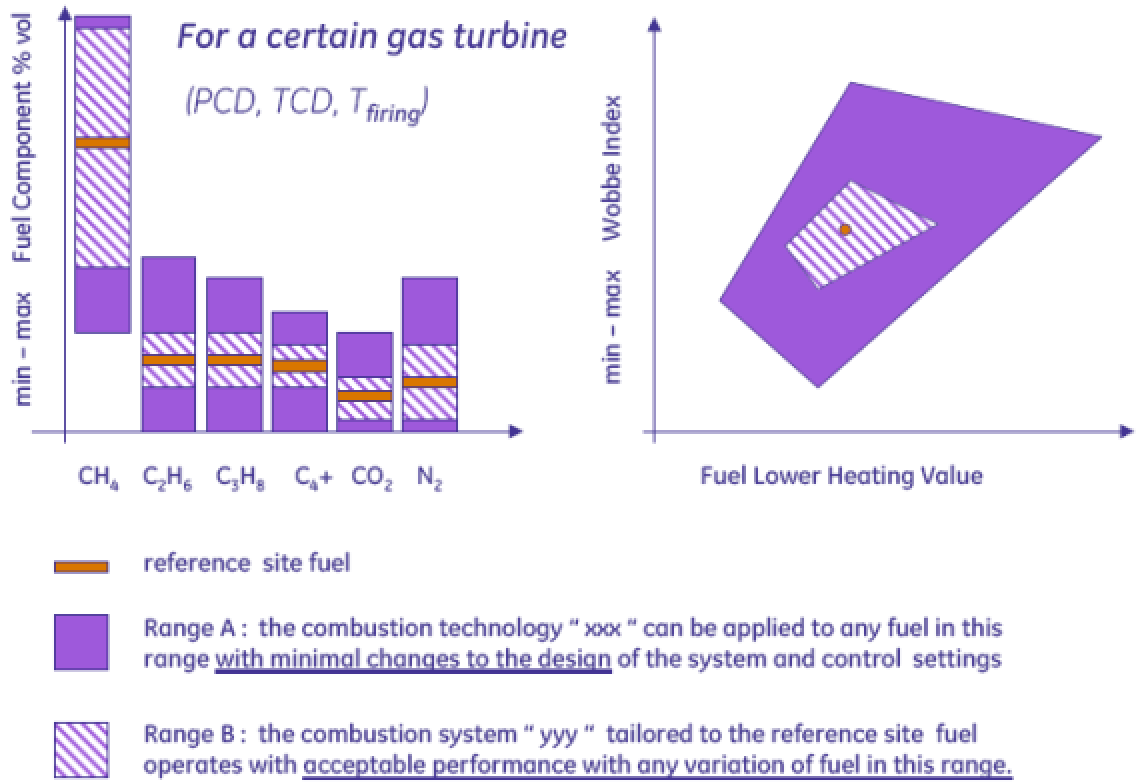

Figure 2**: Definition of Fuel Flexibility**

Once a system is optimized for the site's reference fuel, the configured hardware has a limited range of fuel flexibility, Range B. Fuel composition changes that remain within Range B are acceptable and the performance of the system is guaranteed. Unfortunately, for high-efficiency low-emissions lean premixed combustion systems of today, Range A includes the vast majority of natural gas fuels but excludes most of the fuels in Table 1. Range B is even more tightly limited within this space. As mentioned earlier, almost all of the fuels in Table 1 can be utilized for gas turbine operation – that is, the window for Range A can be shifted to include almost any specific fuel using diffusion combustor technology. The goal of this research program is to expand Range B for lean-premixed combustion systems, such that it encompasses natural gas as well as a significant fraction of the fuels in Table 1.

3.4 Sources and Applications

3.4.1 Syngas / gasified fuels

Solid or liquid fuels can be converted to a gaseous form ("synthesis gas or syngas") through gasification – a reaction process by which the feedstock is partially reacted or combusted in a fuel-rich / oxygen-starved atmosphere. This process converts the hydrocarbon fuel components to a gas mixture typically made up of H_2, CO, CO_2, CH_4, N_2, and H_2O, while the mineral or ash components of the feedstock agglomerate and are removed from the process stream. The actual composition of the synthesis gas depends, in part, on the feedstock itself – its ratio of hydrogen to carbon, moisture content, and fuel-bound nitrogen content. More importantly, however, the type of gasification process and its operating parameters affect syngas composition and therefore its combustion properties. A detailed discussion of gasification is outside the scope of this program; however, a few comments are provided here as it pertains to the categories of syngas fuels.

3.4.1.1 Gasification methods

There are three important gasification methods: air-blown gasifiers, O_2-blown gasifiers, and indirect-fired gasifiers. In the first two, the fuel is directly combusted with an oxidant, and the heat produced from the partial oxidation of the feedstock provides the high temperatures to drive the reaction chemistry. In the indirect-fire method, a separate fuel stream is burned to heat the reactor vessel and steam is often used as the oxidizing agent for the feedstock. Direct-fired gasifiers can be operated at near-atmospheric pressures (typically a few psig) or at elevated pressures (up to at least 30 atm). The choice between atmospheric or pressurized gasifiers will depend on the costs of compression of the oxidant, the challenge of dry feeding a pressurized biomass or the lower heating value of pressurized wet slurry, the temperature and pressure requirements or limitations of the syngas fuel conditioning equipment, and the costs of syngas compression to feed the gas turbine. The temperature at which the gasifier is operated also has an impact on the final syngas composition, with higher reactor temperatures driving faster reactions but also producing a lower syngas heating value due to the higher CO_2 content (more of the fuel energy content is consumed in heating the gasifier).

Air-blown gasifiers are the simplest gasifiers to operate; however, they also create a syngas with the lowest heating value of the three methods due to the high N_2 content. O_2-blown gasifiers, pressurized versions of which are the backbone of current coal-fired Integrated Gasification Combined Cycle (IGCC) plants, produce a higher heating-value syngas. These gasifiers require an onsite air-separation unit to provide the O_2 for gasification, adding considerable capital and operating costs to the gasification facility. Indirect-fired gasifiers produce the highest heating-value syngas, typically without significant N_2 content and lower CO_2 content than direct-fired gasifiers. In addition, the steam reforming in an indirect gasifier increases the H_2 content of the gas. Due to the lower operating temperatures of indirect-fired gasifiers, the reactor can be made from non-refractory materials. However, these gasifiers suffer at least one disadvantage in that they result in increased formation of tars – large hydrocarbons that must be removed via conversion to smaller, lower boiling point hydrocarbons in a thermal or catalytic tar cracker. The next section provides a summary of the fuel characteristics of the different gasified fuels.

3.4.1.2 Biomass

The largest impact on natural gas usage in industry is anticipated to be a result of biomass and gasification consumption (Booz-Allen-Hamilton, 2007), with an estimated near-term natural gas displacement potential of 4,000 TBtu/yr (Table 1-1 in (Booz-Allen-Hamilton, 2007)), and industry-specific anticipated natural gas displacements of ~74 TBtu/yr by 2012 in the food, paper (including black liquor), and chemical industries (Table 5-1 in (Booz-Allen-Hamilton, 2007)). Biomass is available in several forms, primarily categorized as either agricultural or forestry biomass. Agricultural sources include crop residues – corn stover (stalks and leaves), wheat straw, and rice straw. In the long-term, the cultivation of dedicated energy crops such as switchgrass may also become important. Forestry biomass includes forestry industry residues (sawdust and chips – used already by milling operations as a fuel source), slash (material pulled from the forests but not used for products, including tree tops and leaves), and potentially expanded logging. Biomass utilization will likely be focused in specific regions of the United States: the Midwest for agricultural residues, and the southeast, northeast, northwest, and north central areas for forestry residues.

Biomass must be gasified (bio syngas or BSG) for use in gas turbines. There are many small industry-scale gasifier companies and several processes for gasifying biomass. Generally, the biomass is dried, ground up, and gasified; followed by syngas cleanup to remove particulate matter, alkali and heavy metals, halide compounds, nitrogen and sulfur compounds; and conversion of heavy hydrocarbons, or tar, to smaller gas-phase hydrocarbons. It is the management of tars, much more prevalent in gasified biomass than in other gasified feedstocks, which proves to be one of the biggest challenges to biomass gasification (Kiel, 2004).

3.4.1.2.1 Fuel characteristics

Characteristic compositions of gasified biomass are shown in Table 2 (Table 3 of (Zwart, 2003), converted into English units):

Table 2: Sample bio syngas compositions.

		Indirect (Batelle)	Atm. air blown	Atm. O2 blown	Press. O2 blown
CO	[vol %]	41.5	19.2	26.6	15.9
H2	[vol %]	22.5	15.4	32.8	17.9
CO2	[vol %]	12	14.8	29.5	34.8
CH4	[vol %]	16.2	4.2	7	13.3
N2	[vol %]	0.1	43.8	0.7	12
Ar	[vol %]	0	0.5	0	0
C2H4	[vol %]	0	1.4	2.3	4.4
C6H6	[vol %]	5.4	0.3	0.6	1.1
H2S	[vol %]	0.000453	0.000169	0.000305	0.000351
COS	[vol %]	0.0005	0.000019	0.000034	0.000039
NH3	[vol %]	0.005714	0.002135	0.002744	0.003158
HCl	[vol %]	0.000345	0.000129	0.000212	0.000244
HF	[vol %]	0.000045	0.000017	0.000028	0.000032
Tar	[vol %]	0.031489	0.009228	0.01175	0.018884
LHV	[Btu/scf]	501.4	186.3	312.5	348.2
HHV	[Btu/scf]	538.7	201.1	340.6	378.5
MWI		25	7.8	13.9	14.2
CGE*		80.4	79.1	80.6	79.1

*Cold Gas Efficiency (CGE) is defined as the ratio of the syngas HHV compared to the original HHV of the biomass feedstock.

The above fuels, along with other representative fuel compositions for various gasifier types, are graphed in Figure 3. The grouping of the three gasifier types becomes quite evident.

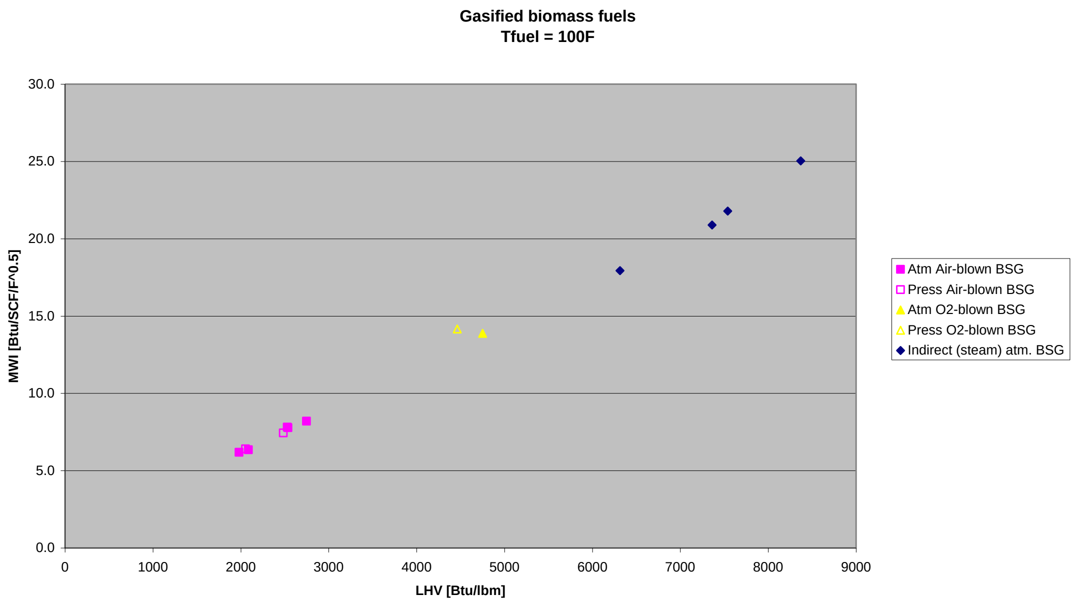

Figure 3: Representative gasified biomass syngas.

3.4.1.2.2 Utilization in gas turbines

Syngas fuels, in particular those produced in large utility-scale coal-, oil-, or pet coke-fired gasifiers, are currently utilized in many locations to fire heavy duty (HD) gas turbines in power and cogeneration installations from 12-550MWe (Brdar & Jones, 2000). Current technology for burning these fuels is a standard non-premixed combustor, with diluent injection (typically N2, water, or steam) to control peak flame temperatures and therefore NOx emissions. GE also has explored the operation of an industrial aeroderivative (IAD) gas turbine on gasified wood biomass [(Neilson, LM2500 Gas Turbine Modifications for Biomass Fuel Operation, 1998)**,** (Neilson, Shafer, & Carpentieri, LM2500 Gas Turbine Fuel Nozzle Design and Combustion Test Evaluation & Emission Results with Simulated Gasified Wood Product Fuels, 1998)]. This project included a full annular combustor test at 1 atm and a 5-nozzle sector high-pressure combustion test to explore the operation of the combustor on syngas fuels in the range of 140-180Btu/scf. The fuel nozzle used was a modified diffusion fuel nozzle for a single annular combustor (SAC), including dual fuel circuits for the startup fuel (propane or LPG) and the low-Btu fuel. Combustion performance was investigated at up to 50% load conditions using 100% bio syngas fuel without any added diluent.

Gasified biomass power plants have historically averaged in size at ~20MW (Brian, Amos, Downing, & Perlack, 2003). With improved collection techniques and transportation infrastructure, this plant size may increase; however, the economics of transportation and collection and the fraction of land available will ultimately limit the biomass available at any given location. Current gasifier projects are primarily 30MW and smaller. Utilization of gasified biomass as 100% of the fuel in gas turbines will likely involve medium-size gas turbines in the 20-80MW range, with larger turbines potentially requiring co-firing with natural gas to make up for the availability of biomass.

3.4.1.2.3 Fuel end-users

Potential customers for new biomass-fired gas turbine power plants or retrofit of existing power plants for utilization of biomass may cover the spectrum of distributed grid power generation to industrial power consumption. Forestry product residues, currently used by the industry to offset fossil fuel usage, could alternatively be gasified for more efficient onsite power generation. The exact market size is unclear, as much will depend on the price of fossil fuels, CO2 regulations, and government incentives. However study by (Booz-Allen-Hamilton, 2007) suggests near-term ~74TBtu/yr of natural gas substitution in food, paper 25MWe simple cycle output power for industrial use alone. These machines would likely supply base load power to the plant, as the startup and shutdown of the gasifier would probably not be cycled frequently.

3.4.1.2.4 Backup fuel

It is assumed that for industrial applications of gasified biomass for site power, the operator will require the capability to operate the power generation system on 100% backup fuel such as natural gas or a liquid fuel oil, in full emissions compliance, in order to reduce the risk of a plant shutdown due to gasification component failure or biomass availability. Natural gas is going to be assumed as the backup/startup fuel for the present research program. Emissions requirements for the gas turbine will depend on the local area in which the plant is located, and also may depend on the size of machine and whether the fuel is natural gas or non-natural gas. Generally, new technology must strive to meet the requirements of the most stringent market it will be sold into.

Current syngas combustion systems require a conventional fuel for startup and shutdown. It is assumed that this will be the case for new technology development, but keeping in mind that operation on 100% syngas over the full operational range is a desirable capability.

3.4.1.2.5 Development directions

GE currently has had much success in operating IGCC gas turbines on syngas, utilizing diffusion flame combustion technology and diluent injection for NOx abatement (Brdar & Jones, 2000). Further desired advances in technology include lean-premixed Dry Low NOx (DLN) capability in order to eliminate the requirement for diluent, with F-class efficiencies. In addition, it is desirable to utilize bio syngas successfully in lean-premixed Dry Low Emissions (DLE) combustion systems for industrial aeroderivative turbines, with their attractive high pressure ratios and efficiencies.

3.4.1.3 Black Liquor

Black liquor is a product of the pulping process in paper mills, consisting of a chemical mixture used to pull the lignin out of the wood pulp. The removed material contains roughly half of the energy content of the wood feedstock, and thus has been used by the paper industry for years to fulfill part of their energy requirements. The black liquor is typically concentrated to somewhere near 70-80% solids loading and then burned in a recovery boiler. The boiler is used to raise steam for process heat in the plant and/or to drive a steam turbine for plant electricity generation. The inorganic material in the black liquor is recovered and reused in the pulping process. Paper mills also operate separate power boilers, fueled with scraps from the wood yard and/or a purchased fuel such as fuel oil #6, which raise steam for local power generation.

(Larson, Consonni, & Katofsky, 2003) have performed an extensive economic tradeoff study regarding the gasification of black liquor and combined cycle power generation for paper mill energy requirements. Due to the low efficiency of the existing boilers (~20-25%), much improvement can be gained through gasification and combustion in a combined cycle, potentially eliminating the plant's need to purchase fuel or electricity from outside sources and even opening the possibility of selling excess power back onto the grid. Because this fuel is a process waste stream, it is one of the strongest examples of local production/local use.

Black liquor gasification is challenging on at least two fronts. First, a significant criterion of the process is to recover the valuable inorganic materials from the black liquor for reuse in the plant. Second, the caustic nature of the black liquor can create challenges for the gasification system. Even so, two companies are currently developing and demonstrating technology for black liquor gasification: Chemrec (http://www.chemrec.se/), providing a pressured air-blown gasifier, and TRI (http://www.tri-inc.net/index.html) developing an indirect-fired low temperature process that generates syngas with a higher LHV. Both companies have built demonstration plants in the U.S., TRI in association with Georgia-Pacific Corporation, and Chemrec with Weyerhaueser Company.

3.4.1.3.1 Fuel Characteristics

Example syngas compositions and combustion properties are taken from Table 4, Section 5.3 of (Larson, Consonni, & Katofsky, 2003) and shown in Table 3.

Table 3: Syngas compositions from black liquor gasification

		TRI Low T Indirect (steam)	ChemRec High T,P Direct (O2)
CO	[Vol %]	23.74	26.09
H2	[Vol %]	61.91	27.51
CO2	[Vol %]	10.5	11.27
CH4	[Vol %]	3.49	1.44
N2	[Vol %]	0	0.24
Ar	[Vol %]	0	0.66
H2O	[Vol %]	0.34	32.73
C2H6	[Vol %]	0	0
LHV	[Btu/scf]	278	173
MWI	@ 100F	17.5	8.9

As can be seen in Figure 1 and in comparison Table 1, the syngas compositions from black liquor gasification are similar to biomass syngas, except that the indirect-fired black liquor syngas has higher H2 content and therefore slightly higher LHV on a mass basis.

3.4.1.3.2 Utilization in Gas Turbines

The applicability of gasified black liquor for use in GE gas turbines is essentially the same as for gasified bio syngas. The availability at a given site appears to be at least up to 80MW, as this is the mill-scale gas turbine modeled by (Larson, Consonni, & Katofsky, 2003). The potential end-users of this fuel are strictly limited to the paper and pulping industry. While the paper industry is significant in the U.S., Table 5-1 in (Booz-Allen-Hamilton, 2007) indicates

that roughly 34 TBtu/yr might be expected for fuel switching away from natural gas and toward gasified biomass in the near future, including the use of black liquor.
All of the other issues related to the end-use of this fuel in gas turbines and the technology gaps are similar to that given in Section 3.4.1.2.

3.4.1.4 Municipal Solid Waste

Municipal solid waste has possibly the third highest near-term natural gas displacement potential, next to biomass and coal, at an estimated 1,350 TBtu/yr (Table 1-1 in (Booz-Allen-Hamilton, 2007)). This fuel source benefits from the fact that it is already collected in a centralized manner all over the country, but is challenged by the heterogeneous nature and variability of the fuel content. After any recoverable materials such as metals have been separated out, organic components of municipal waste are gasified either by partial oxidation in pure O2 or through the use of plasma technology to add very high temperature heat, and potentially reactive species, into the reactor. The elements in the waste are thus converted into syngas.

3.4.1.4.1 Fuel characteristics

Due to the natural widespread variability in municipal waste content from location to location, the syngas content also varies significantly in different locations. Table 1 and Figure 4 give an indication of the range of syngas compositions possible, given a selection of elemental compositions taken from several different cities. The elemental compositions and reactor assumptions were fed into an O2+plasma gasifier model in order to predict the syngas composition. As can be seen in Table 1 and Figure 4, the range of syngas characteristics spans from the O2-blown biomass and black liquor syngas down into the range of air-blown syngas.

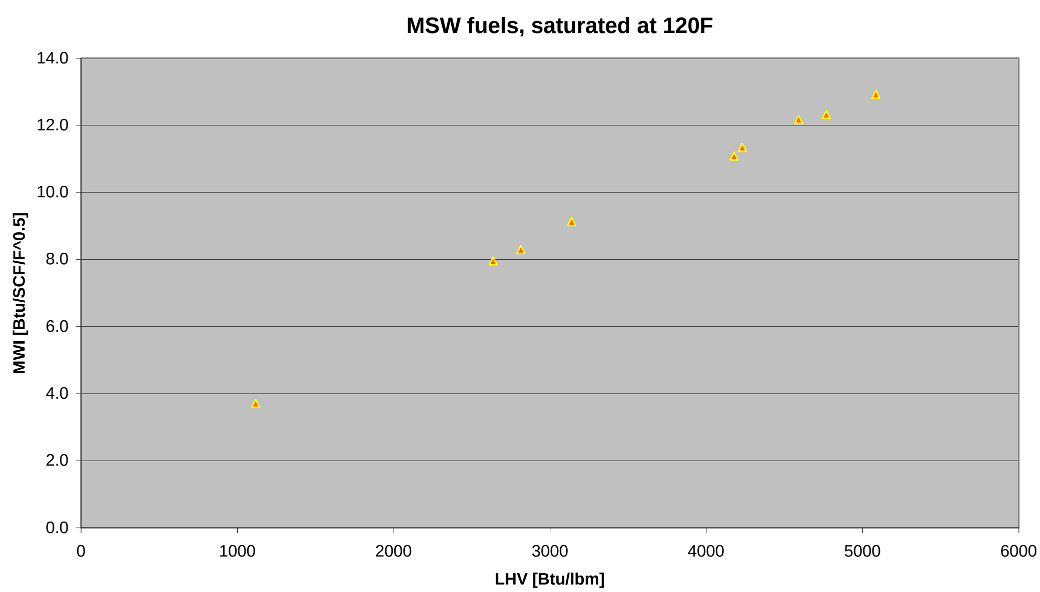

Figure 4: Wide variability in MSW syngas compositions

3.4.1.4.2 Utilization in gas turbines

The applicability of gasified municipal solid waste in gas turbines is similar to that for other syngas fuels, with the added potential for even stronger fuel variability at a given location. GE has addressed the challenges of using this fuel in one of our aeroderivative engines, the LM2500+G4, for an installation at the Malagrotta landfill outside of Rome, Italy. This machine is a diffusion-flame combustor with water injection to control NOx emissions, generating up to 32MWe. Available fuel at a given site will not doubt cover a very large range, however the site examples used for calculations in Figure 4 range from 30 to 145MW capability, given the modeled syngas flow from the gasifier. Potential customers for waste gasification/power generation facilities may be waste management companies or independent power producers. Waste management companies have the collection infrastructure, as well as currently bearing the burden of paying for landfill dumping of waste.

Aside from the potential for increased fuel variability with this feedstock, all of the other issues related to the end-use of this fuel and the technology gaps are similar to that given for biomass syngas in Section 3.4.1.2.

3.4.1.5 Petroleum coke

Petroleum coke, or petcoke, is a byproduct of the petroleum refining process. The authors of (Booz-Allen-Hamilton, 2007) estimate its near-term natural gas displacement potential to be second only to biomass, at 525 TBtu/yr. By 2012 the projected actual natural gas displacement via use of petcoke is anticipated to be 50 TBtu/yr. The most likely end user will be the refinery source itself, although petcoke can be transported and used like coal, and even has some advantages compared to coal (see Table C-1 of (Booz-Allen-Hamilton, 2007)).

Petcoke is gasified similar to coal, for example in pressurized O2-blown gasifiers. The syngas therefore has a similar composition to other O2-blown syngases (see Table 1), although it tends to be higher in CO and somewhat lower in H2 compared to many O2-blown syngases. Aside from differences in the local use of the petcoke, all of the other issues related to the end-use of this fuel and the technology gaps are similar to that given for biomass syngas in Section 3.4.1.2.

3.4.2 High-inert or Weak Natural Gases

3.4.2.1 Digester gas

Digester gases are produced from wet waste streams such as agricultural wastes (e.g. manure), industrial wastes (e.g. food processing), or municipal wastes (e.g. sewage/water treatment plants) through the process of anaerobic digestion. The result is a gas that is primarily 60-70% CH4 with a balance of CO2, creating a medium-Btu gas that is ready for use in a combustion turbine. Digester gases can be produced just about anywhere, from a multitude of feedstocks, and in widely varying quantities from location to location. Table 1 gives typical digester gas compositions.

3.4.2.1.1 Utilization in Gas Turbines

As digester gases are typically produced in smaller quantities, they have not been widely utilized in medium- to large-scale gas turbines. However, their fuel heating value is adequate for gas turbine operation. As with all opportunity fuels, in small quantities digester gases can be blended in with natural gas and fired in today's most advanced lean premixed combustion systems with no loss in performance. Large quantities of digester gas can be utilized in diffusion-style combustors whose fuel nozzle orifices have been appropriately sized for this fuel type, with the addition of diluent to control NOx emissions.

The market size is not established for this fuel source. However, GE has multiple active inquiries from both industrial customers as well as municipal customers for either blending the gas with 95% natural gas fuel heating content (an industrial customer) or for firing 100% digester gas (a municipal customer) – both applications being for 23-40MW sized turbines. Depending on the customer, the machine may be used to supply local power to an industrial plant or grid power. Base load and part load operation down to 50% of max power is desired, while staying within emissions compliance. Due to potential interruptions in digester gas supply, the machines must be robust enough to accommodate an increased fraction of backup fuel to maintain power generation. They also must tolerate seasonal changes in the availability of the digester gas.

Existing gas turbine technology (diffusion combustors with diluent for NOx abatement) is available to burn these fuels. However, DLN or DLE technology is preferred for low emissions benefits as well as the elimination of diluent requirements.

3.4.2.2 Landfill Gas

Landfill gases (LFG) are primarily composed of 40-60% methane diluted with CO2. The fuel composition lays in the same region as other high-inert natural gases in Figure 1, and its combustion poses similar challenges as those gases. In a database of over 500 landfill gas installations, only 14 installations produce power above 10MW. This area is well served by microturbines and especially reciprocating engines, the latter demonstrating low capital cost and high efficiencies. As with all the opportunity fuels, small amounts of LFG can be blended with pipeline gas and readily burned in larger gas turbines for power generation.

3.4.2.3 Coal Methane

Methane obtained from coal mining operations comes in 3 or more forms. "Coal bed methane" is obtained during the initial mine opening process. This gas is often over 90% CH4, and can typically be injected into standard natural gas pipelines. "Coal mine methane" has higher diluent content, making it a medium Btu gas. It is challenging to use due to its temporal variability in composition. "Abandoned mine methane" may have a slightly higher Btu content than coal mine methane, but still has high diluent content. There are very few mines that produce more than 10MW worth of coal-based methane, and most of these applications are already being well served by reciprocating engines, which are efficient and quite tolerant to fuel-composition variability. The utilization of coal-based methane in a gas turbine is an opportunity similar to landfill gas, in that it is likely to require blending with natural gas in order to fuel gas turbines with output 20MW and higher.

3.4.2.4 Weak Natural Gases

Oil and gas companies have a lot of weak or highly diluted natural gas that is produced in the field during processing or upgrading of fuel before injection into the pipeline. These fuels can have high diluent content - up to 60 or 70% N_2 or CO_2, making them difficult to burn in today's DLN or DLE combustion systems due to their low reactivity and flame speed. While they might be burned in a conventional diffusion combustor, this technology requires diluent injection to meet NOx regulations. In many locations, water is scarce and it would be preferred to utilize these fuels using Dry Low NOx or Dry Low Emissions combustion technology. While the LHV and Wobbe index are similar to that for indirect-blown or O_2-blown gasification fuels (see Figure 1 and Table 1), these two fuel groups have quite different combustion parameters due to the high H_2 content and high flame speeds inherent in syngas fuels. High-inert fuels have the same challenge as syngas regarding the requirement for large volumetric flows of fuel, however their low reactivity makes flame stabilization a significant challenge (unlike in high-H_2 fuels, where flame-holding near the nozzle is a primary concern).

High-inert fuels from natural gas fields are a significant opportunity for fuel-flexible combustion systems. Large natural gas fields may employ multiple gas turbines for mechanical drive compression or other fuel processing operations. Typical gas turbine sizes can be in the 25-80MW class size or higher. The machines are typically utilized in a constant operation mode, with an installation usually having a little more capacity than required to compensate for loss of a machine for maintenance. Therefore, the machines will typically be running at a constant load of 70-100% of their maximum output capability, with desired operation on 100% opportunity fuel. Customers require that the machines operate to specifications on 100% pipeline gas or other conventional fuel as a backup.

Ongoing tests continue to investigate the limits of our DLN and DLE combustion systems to operate with high levels of inert components in these weak fuel gases. However, to achieve 60-70% diluent levels, new fuel nozzle concepts will be required to enable mixing of the high volumetric flow rate low-Btu gas while maintaining flame stability and low dynamics.

3.4.3 Blast furnace gas and coke oven gas

Blast furnace gas (BFG), generated in steel mills, is the weakest of all fuels considered in this program. Typical composition and combustion parameters are given in Table 1. BFG cannot be fired at F-class conditions even in stoichiometric fuel-to-air ratios, and is very challenging to combust as a pure fuel. The largest market for the utilization of this fuel is in China, with some inquiries occurring in the U.S. Ongoing programs at GE are already working to address this challenging fuel, and aside from an assessment of the potential for plasma enhanced flame stabilization of this fuel, it is not considered an important target fuel for this development program.

Coke oven gas (COG), with its very high H_2 content, is much easier to burn from a flammability standpoint, but has challenges similar to syngas in that it has a very high flame speed. It is typically used in small quantities along with BFG in order to facilitate the use of the BFG stream; however the customer would prefer to use this high-value gas stream for other purposes. It is not viewed as an important gas turbine fuel to be considered in this program.

3.4.4 Rich refinery off-gases

The final category of fuels considered for this program is rich refinery off-gases. These fuels are fed into an off-gas header at a petroleum refinery, and would ideally be used to offset the natural gas usage for the refinery's power requirements. These fuels are characterized by high content of higher hydrocarbons (C2-C5+), high H_2, occasionally high inert gases (N2 or CO2), or a mixture of all of these. The fuel composition in the off-gas stream can vary widely depending on the processes being run at a given point in time, the feedstock of various processes, or even the season of the year. Refinery customers would like to use as much of this gas as possible to offset their own energy costs, rather than flaring the off-gas. However, current DLN or DLE combustion system operating specifications limit the Wobbe index variation within a tight tolerance (typically +/-5%) around a given set point. Content of certain species, especially H_2, is also limited in these combustion systems, thereby limiting the fraction of this opportunity fuel that can be blended with natural gas. The only fuel preparation requirement for the use of these fuels is that they be preheated sufficiently to meet superheat requirements and prevent liquid fuel condensate from being formed in the fuel system. Some example refinery gas composition limits are shown in Table 1 and plotted in Figure 1. These gas mixtures are characterized by high Wobbe index (mixtures with high HC content) and high LHV [Btu/lbm] (for mixtures with high H2 content) compared to standard natural gas. In addition, the high H2 content makes these fuels significantly more reactive, leading to challenges of flame holding and flashback in lean premixed combustion systems.

4 Fuel Flexible Combustion System Development Targets

An important characteristic of the combustion development goals in this program is the desire for the new technology to obtain emissions-compliant operation in lean-premixed mode on both the opportunity fuels as well as on natural gas. This fuel-flexibility is the primary development goal and challenge for this research program.

4.1 Target Fuels of Interest

Based on the assessment of the opportunity fuels space, and comparing the market opportunity with current technology capabilities, the following fuel groups were identified as the target compositions for fuel-flexible lean-premixed nozzle development effort.

Target fuel space:

- Low Wobbe/Low LHV fuels
  - High-inert Nat. Gas (digester gas, LFG, weak natural gas fields)
    - Typical components: N2 or CO2 / balance CH4 (Nat. Gas)
  - Low-Btu syngas (air-blown gasified biomass, black liquor, petcoke, MSW)
    - Typical components: (H2 / CO / CH4 / CO2 / High N2)
  - Med-Btu syngas (O2-blown gasified biomass, black liquor, petcoke, MSW)
    - Typical components: (H2 / CO / CH4 / CO2 / Low N2)

- Satisfactory operation on Natural Gas is a requirement.

Another development target will be technology demonstrations of concepts for operating fuels spanning the range from low Btu/Wobbe to high Btu/Wobbe employing single nozzle architecture. The developed machine must be capable of operating at full load on 100% natural gas as backup fuel, while remaining in full emissions compliance. Variability between 100% NG and 100% opportunity fuel is needed for fuel nozzle commonality, although many applications will know their target opportunity fuel blend ratio due to upstream process capabilities.

4.2 Fuels Conditioning

The fuels of interest may, in final applications, arrive at the gas turbine with some moisture content and some level of preheating. The effects of fuel preheating are well known (Erickson, Day, & Doyle, 2003). Performance heating of the fuel can be applied at temperatures approaching 400F, using feedwater extraction from the heat recovery steam generator (HRSG) at an optimum location in a combined-cycle power plant. Such heating generally leads to improved plant thermal efficiency due to the lower fuel flow requirement to reach the gas turbine firing temperature. Fuel preheating using gas-fired, oil-fired, or electric preheaters is also possible, but this has a negative impact on the plant efficiency. In addition to performance heating, some moderate fuel preheating is also required in order to maintain a minimum margin of superheat for any condensable constituents in the fuel (Specification for Fuel Gases for Combustion in Heavy Duty Gas Turbines, 2007). Fuel preheating can also be used as a control variable in order to fine-tune the gas turbine controls for optimal combustion dynamics and emissions performance, providing some flexibility in the system for small variations in fuel composition as well. Finally, the compression process for some fuel feedstocks may also raise the temperature of the gas, depending on the required level of compression and other fuel conditioning options. For different combustion systems, fuel preheating may be applied throughout the operating envelope or sometimes only in operating modes in the upper 50% of the load range.

Fuel moisture content is another unprescribed variable. Most pipeline gases have negligible moisture content. However, gasification products and many process off-gases can have, by their nature, significant fractions of H2O as a constituent. The present-day technologies for cold-gas cleanup of gasification products can result in much of the water content being removed from the syngas during scrubbing processes; however, this is highly dependent on whether the system operates at high-pressure or low-pressure. If the gasification train operates near 1 atm, the final moisture content will also depend on the fuel gas compression process and whether the moisture is removed via an intercooler and water drop-out between stages. In large-scale IGCC plants, additional moisture is often added to the fuel or injected directly into the gas turbine combustor for both power enhancement as well as NOx reduction (Brdar & Jones, 2000).

Hot-gas or warm-gas cleanup technologies are also being developed for the conditioning of gasification products. Such technology is particularly attractive for air-blown gasifiers, due to the efficiency loss and capital costs of heating up and cooling down the N2 in the syngas [6]. Hot- or warm-gas cleanup technologies would retain both sensible heat and moisture in the syngas flow, requiring less fuel and generating more power for the same amount of fuel feedstock. There are, however, many significant technical and commercial challenges yet to be overcome if these technologies are to become realized (Simbeck, 2002).

For the purposes of this program, the fuels are assumed to be essentially dry and at low temperature, ~ 100F. The final application and fuel conditioning options chosen by a customer will be highly site-specific, dependent upon the secondary flows available in the plant for optimization and the status of new technology development such as hot gas cleanup for syngases. Regarding fuel-flexible premixer design and development, fuel preheating in a gas turbine installation will impact the fuel pressure requirements and thus fuel injection pressure ratios, as well as causing some increases in premixed flame speed and flameholding/flashback risk. Fuel moisturization affects fuel volumetric flow requirements, and will have similar effects on flammability limits and NOx emissions as does increased content of other fuel inerts such as N2.

4.3 Combustion System Performance Targets

1) Combustor operating conditions will be appropriate to the given machine or machines as down selected during the cycle analysis. Depending on H2 content in the fuel, the firing temperature may need to be limited to protect hot gas path hardware from excessive thermal loads due to high mass flow rates and H2O content. Also, the combustor pressure drop must be assessed to assure adequate 1st stage nozzle cooling backflow margin. The early cycle modeling will help to assess these combustion conditions based on the target fuel compositions and specific machine operating lines.
2) Startup fuel will be pipeline natural gas for simplicity in this study. It is assumed that the intended backup fuel may also serve as the startup fuel. Ignition capability / limits on opportunity fuels will be assessed, but is not a required performance criteria. Ignition envelope on startup fuel will be assessed, and must be within typical requirements of the machine.
3) Flame holding/flashback: The fuel nozzle must meet flame holding and flashback margin requirements at all conditions, according to standard GE design practices.
4) Durability: The fuel nozzle must meet accepted design criteria for materials.
5) Turndown: Operating requirements will be a minimum emissions-compliant turndown to at least 50% of base load using opportunity fuel only.
6) LBO/dynamics margin will be assessed during program, and will be targeted to be comparable to existing lean premixed technology across the operating envelope.
7) Combustor dynamic pressures will be measured and targeted to maintain levels comparable to allowable levels for the gas turbine.
8) Price for combustion hardware should be comparable to existing gas turbine offerings.
9) Emissions requirements will be appropriate to current U.S. regulations for gas-fired turbines.

4.4 Fundamental Data Targets

This research program also has the goal of improving our understanding of fundamental physical transfer functions between fuel nozzle design parameters and performance. These findings are critical to making the current development program results applicable over the long term for new fuel nozzle design and development. Examples of this required data include:

- Parametric study of plasma-enhancement capability for opportunity fuels

- Premixer efficiency for various fuel injection methods; understanding of fundamental limitations (if any) on acceptable MWI range for a fixed piece of hardware. Combustion efficiency limits on variable fuels with fixed hardware
- NOx entitlement for perfectly premixed fuels
- Exploration of variable flow splits – enabled by mechanical/fluidic actuation

4.5 Target Machine Architecture

The following GE gas turbines fall within the size range of most interest to many opportunity fuel applications.

Aeroderivative class:
- LM2500/PGT25/25+ (~22-30MW, DLE)
- LM6000 (~40MW, DLE)

DLN1 E-class:
- 6B (~40MW, DLN1/1+)
- 7EA (~80MW, DLN1/1+)
- 9E (~120MW, DLN1/1+)

DLN2 / F-class:
- 6FA+e (~77MW, DLN2.6)

An internal evaluation was performed to determine the most appropriate development platform for new fuel flexible combustion hardware within this research program. Three representative gas turbine combustion systems were considered:

Aeroderivative class:
• LM2500/PGT25/25+ (~22-30MW, DLE)

DLN1 E-class:
• 6B (~40MW, DLN1/1+)

DLN2 / F-class:
• 6FA+e (~77MW, DLN2.6)

Various aspects of these different machines were evaluated, including: previous fuels experience and research programs, ongoing development activities, known combustion challenges and alignment of the technology development needs with the goals and objectives of the current DOE program, known market interest, and the timeline of expected commercialization. Based on these factors, the DLN1+ gas turbine combustion system has been chosen as the focus of our efforts going forward. While this is an E-class system, where it makes sense the fuel nozzle concepts will also be tested at more aggressive F-class or aeroderivative cycle conditions in order to evaluate the capability of specific concepts to perform at higher compressor discharge temperatures and pressures (T3 and P3, respectively), and combustor exit temperature (T3.95) conditions.

The DLN1+ combustion system is shown schematically in Figure 5 (Davis & Black, 2000). This combustion system employs air and fuel staging to accomplish lean premixed combustion and wide operability limits. The combustor modes are illustrated in Figure 6 (Davis & Black, 2000). The Primary Fuel Nozzles themselves provide very limited premixing, and essentially operate in diffusion mode up to 50% load. From 50% load to 100% load, the Primary Fuel Nozzles feed the Primary Zone that now acts as a premixer. The Secondary Fuel Nozzle always operates as a premixing fuel nozzle. Ongoing research and development for this system has pushed its fuel-flexible capability further than other GE DLN or DLE combustion systems, which is one of the dominant reasons why it was chosen as the architecture for the current program. New Primary Fuel Nozzles have already been designed for the DLN1+ and tested using high-H_2 syngases under separately funded research programs. Because these nozzles operate in a diffusion mode at low-load conditions, they produce very stable (albeit high-emission) flames and are robust to flashback/flameholding. Sizing the Primary nozzles for larger fuel flows requires opening up the fuel orifices and/or adding an additional fuel circuit. In addition, this combustion system has undergone some limited testing using natural gas with very high inert levels. In this case, the combustor suffered from lean blow-out challenges as the concentration of inert species increased to the levels of interest for this program.

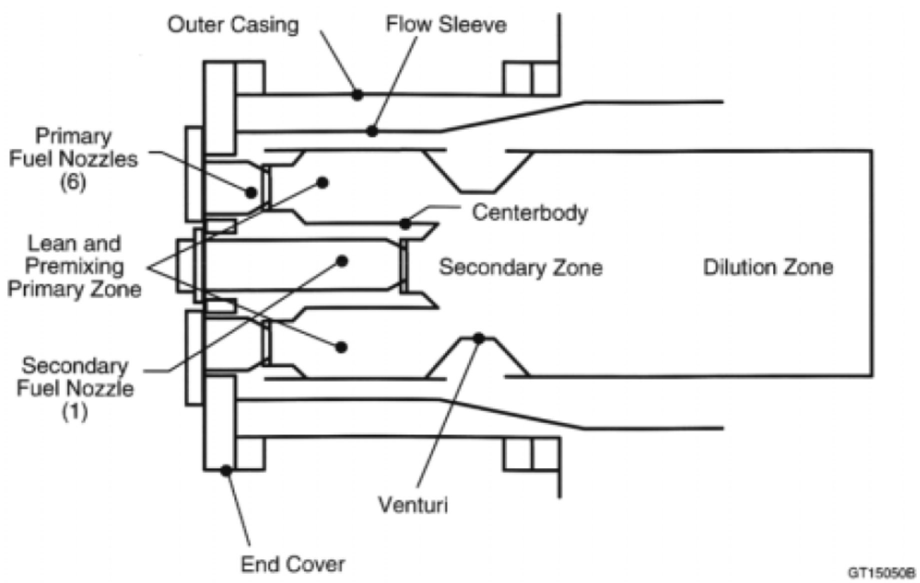

Figure 5: DLN1+ combustion chamber, showing the Primary and Secondary fuel nozzles and the various zones of the combustor (Davis & Black, 2000). Focus in this program will be on the development of advanced fuel-flexible premixers for the Secondary Fuel Nozzle.

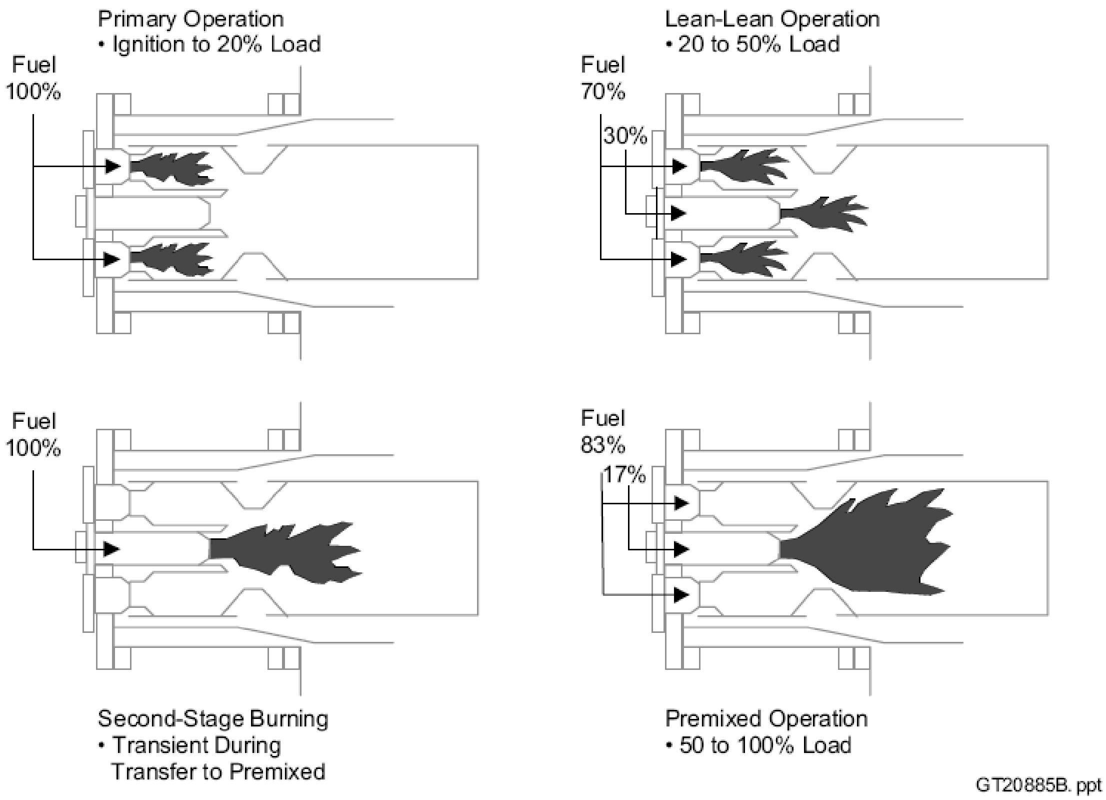

Figure 6: Fuel-staged Dry Low NOx (DLN) operating modes (Davis & Black, 2000).

The focus of the current efforts will be the design and evaluation of advanced fuel-flexible premixer concepts for the Secondary Fuel Nozzle. This is an important development need in order to successfully implement wide fuel-flexible capability for the entire combustion system. Successful designs are expected to be scalable for use in other GE combustion systems in the future.

4.5.1 Fuel Flexibility effects on machine performance and cycle conditions

The fuel flexibility is defined such that an operator can utilize a low-Btu fuel or natural gas interchangeably, requiring no hardware changes. The driver for this type of flexibility is that many of the opportunity fuels considered may exist in limited or time-varying quantities, or they may be subject to varying compositions. Industrial utilization of these fuels requires reliable, emissions-compliant backup fuel capability because the need for onsite power generation remains, irrespective of the type of fuel available. Thus, broad fuel capability reduces the risk of new technology adoption when taking advantage of opportunity fuel resources.

4.5.2 Fuel Flexibility effects on combustor/premixer flows and performance criteria

As illustrated in the previous section, increased fuel volumetric flow impacts the combustor operating conditions. Other challenges occur within the fuel/air premixer itself. In a standard fuel/air premixer with fixed fuel injection orifices, increasing fuel flow demands higher fuel pressures and pressure ratios across the fuel orifices, as shown in Table 4. This can result in non-optimal premixing efficiency, with consequent issues of higher emissions, combustion dynamics and flame stability sensitivity, and increased risk of flashback and flame holding at the fuel injection location. Also, increased fuel mass flow (with fixed injection geometry) typically reduces plant efficiency to boost the fuel pressure. Multiple fuel circuits can be designed to handle each of the various fuels; however this gets complex beyond 2 or 3 circuits, and fuel injection properties of each circuit will still be optimized for a specific design condition or fuel. To hold the fuel injection pressure constant over the range of fuels, the orifice area would have to change by nearly a factor of 9. Novel concepts considered for this program minimizes the impact of varying Wobbe index on fuel injection characteristics and premixing efficiency.

Table 4: Effects of fuel flexibility on premixer fuel injection

Fuel	Wobbe Index (WI)	Molecular Weight	Fuel Velocity ratio of 100% Nat Gas (const. Area)	Fuel Momentum Ratio of 100% Nat Gas (const. Area)	$\Delta P_{fuel}/\Delta P_{NG}$ (const. Area)	A_{fuel}/A_{NG} (const. ΔP_{fuel})	Premix Velocity - Ratio of 100% NG	Combustor Residence Time - Ratio of 100% NG
100% NG	52.5	16.8	1.0	1.0	1.0	1.0	1.00	1.00
40/60 CH4/N2	17.9	23.2	2.8	10.7	10.7	3.3	1.04	0.91
Medium BTU Syngas	11.8	22.5	4.4	26.3	26.3	5.1	1.10	0.91
Low BTU Syngas	7.3	26.2	7.0	75.8	75.8	8.7	1.19	0.75

Another challenge with increased fuel flow is that premixer velocities increase and combustor residence times decrease. While this may be a benefit for high-flame speed, high flame temperature fuels like H2-based syngases, low-Btu and low reactivity fuels may suffer from flame stabilization challenges and CO burnout at these conditions. Changes to the gas turbine control strategy or other air flow handling techniques may need to be employed to assist with variable flame stability properties of different fuels. The challenges of flame stability and CO burnout as fuel is varied will be explored in the entitlement experiments described in Section 6.1.

5 Fuel Nozzle Performance Criteria and Initial Concepts

5.1 *Flame stability predictions via kinetic modeling*

To design a fuel flexible premixing nozzle capable of efficiently burning a wide range of fuels, it is important to properly identify the combustion characteristics of each individual fuel. The impact of fuel composition on the operability of lean premixed gas turbine combustors has been recently reviewed (Lieuwen, McDonell, Petersen, & Santavicca, 2006). Combustion characteristics such as laminar flame speed, lean blow out limits, and ignition delay can all be used as a guide during the premixer design process to help predict flame shape, stability, and safe operating conditions, as well as ensuring that emissions requirements can be met. To obtain these parameters for the current study, chemical kinetics modeling has been performed and the subsequent results are discussed below.

5.1.1 Flame Speed Calculations

Flame speed is a critical combustion characteristic due to its effect on flame stability. Understanding of flame speed vs. fuel composition and operating conditions is used in the prevention of undesirable events such as blowoff and flashback. In addition, empirical correlations exist which allow for the translation of laminar flame speeds into turbulent flame speeds. These turbulent values are then used as inputs to standard combustion CFD codes for prediction of flame stability and shape.

In the current study, laminar flame speeds were calculated for the fuels of interest over the range of operating conditions listed in Table 5. For these calculations, the unburned gas temperature is determined via thermal equilibrium of the mixture of hot air and cold fuel, but an average pressure was used across the fuel space for each of the two load conditions. The GRI-Mech 3.0 (Smith, et al.) chemical kinetics mechanism was used to model the combustion process in the Premixed Laminar Flame-Speed Calculation module of Reaction Design's CHEMKIN 4.1.1 software package (www.reactiondesign.com) and the flame speed results are shown in Figure 7. The results illustrate the fundamental differences between the fuels of opportunity. The Medium-Btu Syngas has the highest laminar flame speed over the calculated range of conditions. In fact, compared to the diluted natural gas (Mixture 2), the flame speed is roughly a factor of 1.5 to 2 greater at a typical flame temperature of 2800 F. This behavior is not surprising due to the high hydrogen content of the fuel (34%). In general, fuels with higher hydrogen content will have higher flame speeds due to the thermophysical properties of hydrogen. In particular, hydrogen has a higher mass diffusivity, thermal diffusivity and faster kinetic pathways than most all hydrocarbons. The behavior of all four fuels at the operating conditions of interest will play an important role in the nozzle design process since flame stability could be challenging when considering such a diverse spectrum of fuels and fuel blends.

Table 5: Nominal cycle conditions used for flame speed calculations at 100% and 50% load

	100% Load				50% Load			
Fuel	CH4	40%CH4-60%N2	MBtu	LBtu	CH4	40%CH4-60%N2	MBtu	LBtu
Tpremix (F)	640	590	550	475	575	530	490	425
P3 (atm)	12.9	12.9	12.9	12.9	8.16	8.16	8.16	8.16

Besides the fuel composition effects on flame speed, temperature and pressure also play a role. A comparison of the 50% and 100% load results indicate that the laminar flame speeds are higher for the 50% load conditions for all mixtures. Flame speeds are both fundamentally temperature and pressure dependent. As stated in (Turns, 2000) the relationship for flame speed is:

$$S_L \propto \bar{T}^{0.375} T_u T_b^{-1} \exp(-E_A/2R_u T_b) P^{-1/2} \quad (2)$$

where, $\bar{T}$, T_u, and T_b are the mean, unburned and burned temperatures, E_A is the activation energy, Ru is the gas constant and P is the pressure. At atmospheric pressure, flame speed is known to have a strong temperature dependence. However, at conditions above 5 atm, (Andrews & Bradley, 1972) have noted that pressure effects can become more dominant. The results of the current study clearly indicate a similar trend. Although, on a mixture-by-mixture basis the 100% load conditions have a higher T_{premix}, the increase in pressure dominates the flame speed behavior and causes the 100%-load flame speeds to be less than at 50% load. This will have implications for medium Btu syngas operation; however, for the other three mixtures, the change in flame speeds from 50% load to 100% load is quite small.

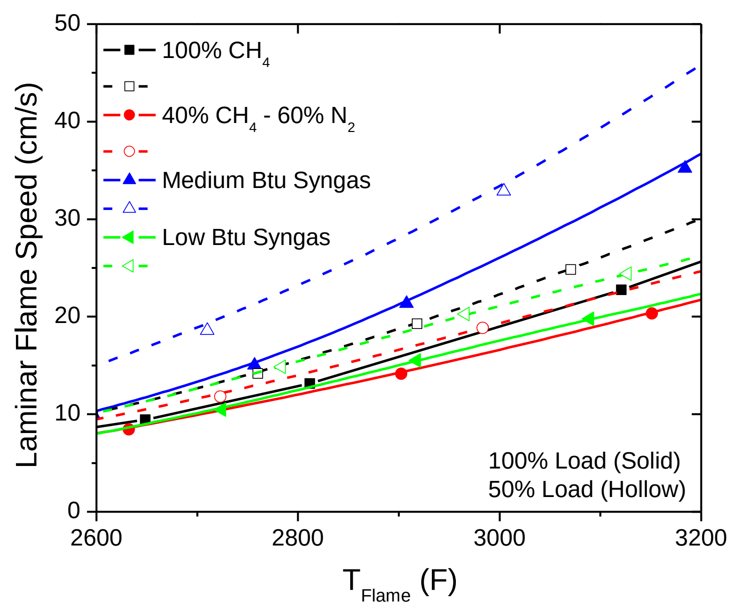

Figure 7: Laminar flame speed calculations of the fuels of interest using GRI-Mech 3.0 at the conditions noted in Table 5.

5.1.2 Stability Limits

In practical devices such as gas turbines, flame stability and blowout prevention are important aspects of engine performance. Stable flames are more efficient and have lower emissions than unstable flames, especially with regards to CO and NOx formation. As industrial gas turbines need to operate under leaner and leaner conditions, the propensity for lean blowout (LBO) to occur becomes increasingly greater. Therefore, tools that can be used to predict the conditions under which a flame becomes too lean are valuable means to ensuring proper engine performance. To understand the stability limits of the fuels of interest in this study, chemical kinetic modeling of the lean blowout phenomenon has been performed.

Using the reactor network shown in Figure 8, the combustion characteristics of a simple gas turbine combustor can be simulated using the GRI-Mech 3.0 (Smith, et al.) chemical kinetics mechanism. This network consists of an inlet, a Perfectly Stirred Reactor (PSR) and a Plug Flow Reactor (PFR). To determine the lean blowout conditions for the fuels of interest, the temperatures and pressures listed in Table 5 were used as input to the reactor network. Subsequently, a parameter study was conducted where the equivalence ratio of each mixture was held constant while the PSR residence time was slowly increased from zero until the mixture ignited and reached the proper adiabatic flame temperature before the exit of the PSR. Beyond this critical residence time, the temperature at the exit of the PSR was no longer sensitive to changes in residence time. This point was considered to be the minimum PSR time needed to achieve a stable flame. Below this value the flame will blow out and stability cannot be achieved.

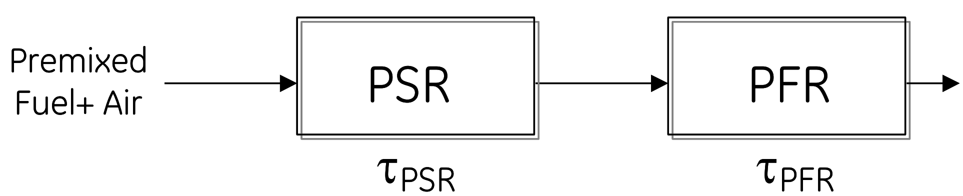

Figure 8: Chemical kinetic reactor network for flame simulation

Figure 9 displays the results of this LBO study for the fuels of interest at the 100% and 50% load conditions noted in Table 5. The space above each of the curves indicates a stable operating condition, whereas below each curve the flame is considered to be unstable and blown out. The medium Btu syngas shows the most turn-down capability since it can reach lower flame temperatures compared to the other three fuels for the same residence time. This is not surprising since the medium Btu syngas had the highest flame speed and flame speed is directly related to flame stability. It can also be noted that the high-diluent methane is the least stable when compared to the other fuels. For an example flame temperature (i.e., 2800F) the diluted natural gas will require 3x the residence time in order to avoid blowoff. This is an important factor and will have an overall impact on the type of combustor that is designed as well as the emissions emitted during the combustion process.

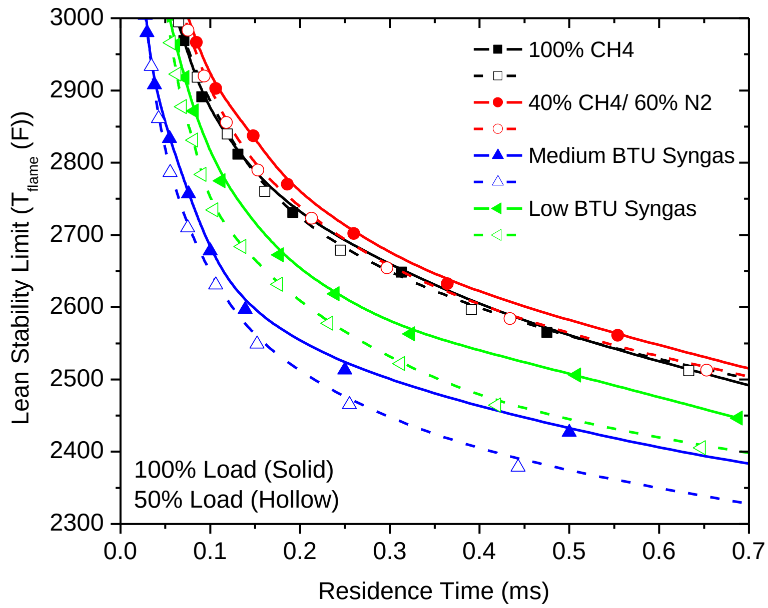

Figure 9: Lean blowout curves for DOE fuels of interest at 100% and 50% load

5.2 Fuel Flexible Combustion Experience – Premixer Challenges

GE has roughly 30 years of experience in development of lean-premixed combustion systems. The overwhelming majority of this work has been focused on standard pipeline natural gas due to its abundance and widespread commercial utilization for power generation. However, as new fuels or fuel variants have gained commercial interest, GE has experience in testing the highly developed baseline combustion hardware using these alternative fuels. Resources such as liquefied natural gas (LNG), which can have higher concentrations of high-hydrocarbon constituents; high-inert natural gases; and small amounts of process off-gases blended into pipeline gas – as well as many other fuels of individual customer interest – have been tested. This experience, which typically examined the flexibility or "wide-wobbe" capability of current production hardware, in addition to externally funded programs, which explore concepts that shift the operational window to new fuel spaces, provide some background experience to guide the present research and development program. In alignment with the objectives of the DOE, the current program's development efforts are now focused on wide interchangeability of fuels in a single, lean-premixed, low-emissions combustion architecture. Wide fuel flexibility is commonly achievable in conventional diffusion-flame combustors, with the concurrent requirement for diluent injection to control NOx and penalty of shorter hardware life due to very high peak combustor temperatures. Wide fuel flexibility in a lean-premixed system, on the other hand, poses a unique set of challenges in order to achieve broad operability and low emissions.

5.2.1 Jet Mixing

A great number of lean premixed combustion systems utilize fuel injection via a jet-in-crossflow arrangement, where the gaseous fuel jet (typically a small volumetric flow) penetrates into a much larger crossflow of air. This mixing strategy permits very rapid mixing across a sizable duct without using physical structures in the flow. In this process, for a fixed geometry, the jet penetration distance is largely controlled by the ratio of the jet momentum flux to the mainstream flow momentum flux (Lefebvre, 1999). Optimal mixing is highly sensitive to the jet penetration distance relative to the duct size of the mainstream flow. Weak jet penetration creates strongly non-uniform mixture profiles downstream of the jet, and full mixing requires a longer mainstream flow length and turbulence. Over-penetration of the jet may cause a number of problems, including interaction of the jet with opposing jets or surfaces – leading again to poor overall mixing. High-momentum jets also generate strong bluff body wakes in the downstream region of the jet that can become locations for flameholding, a condition where the flame can become stabilized near the fuel jet itself, rather than at the exit of the nozzle.

Improper fuel/air mixing in a premixing fuel nozzle can lead to several operational problems for the combustion system. Lean premixed combustion is the industry standard for meeting strict emissions regulations for NOx species, now moving towards permitting levels of 3ppmvd (ref. 15% O2) in many areas of the U.S. However, at the combustor flame temperatures of today's high-efficiency gas turbines, these levels of NOx are achievable only as the combustor head-end approaches perfect premixing. Flame regions that are slightly more fuel-rich than the mean mixture will preferentially drive the production of additional NOx due to the exponential temperature sensitivity of the thermal NOx mechanism.

Another problem with incomplete fuel/air mixing, especially for high-reactivity fuels such as high-H2 syngas, is the risk of flashback and flameholding. Flame speed is strongly dependent on the equivalence ratio, as seen in Figure 7 as well as turbulence intensity levels. The combination of a region of higher equivalence ratio together with low-velocity boundary layers or regions of high turbulence intensity can enable the flame to move upstream into the premixer, potentially causing hardware damage if the flame exists in this location for any length of time. The flame may even become stabilized on the fuel jet or other features in the premixer with local regions of low-velocity or high turbulence. Activity on a DOE-funded research and development program at GE Energy and GE Global Research, focused on gas turbine combustion of H2 and IGCC fuels, has performed significant testing and evaluation of the design requirements for jet mixing of high-H2 fuels (60%-100% H2 by volume) (Advanced IGCC/H2 Gas Turbine Development: DOE Grant DE-FC26-05NT42643, 2005-2014). While the fuels objectives of that program are different from the subject program, the knowledge obtained can be applied to the premixing challenges we currently face for a fuel-interchangeable premixer design that is able to operate on some fuels with higher propensity to flashback than others.

While poor premixing can be a detriment to emissions performance and flame stability for reactive fuels, it can result in a net positive benefit for the weaker fuels. High-inert natural gas (~60% N2 or CO2) has a lower flame speed and also generates lower emissions than the other fuels. The bigger challenge with this fuel is lean flame stability and blow-out limitations. In this case, some level of imperfect premixedness may enable the flame to be more stable while still maintaining acceptable emissions. Non-uniform fuel/air premixedness profiles have also been used beneficially to control combustion dynamics, wherein the flame is more strongly anchored and less susceptible to thermo-acoustic feedback mechanisms that can drive high pressure fluctuations and cause hardware damage. This benefit may be realized across a broader portion of the fuel space.

Comparing the requirements for different fuels in Table 4, it is very clear that, for optimal premixing across a broad fuel space, new methods for fuel injection and mixing must be considered. As the LHV for the fuel decreases, the volumetric fuel flow requirement and fuel molecular weight increase – driving very high fuel jet momentum fluxes. A particular fuel jet geometry and fixed size of injection holes will provide optimal jet penetration and mixing for a very narrow range of fuel specifications – typically only +/- 5% variation in MWI for today's designs. This limitation must be overcome in new fuel-flexible concepts.

5.2.2 Combustion Dynamics

Lean premixed flames can be susceptible to acoustic pressure fluctuations in the combustor. The pressure fluctuations can affect one or both of the fuel injection flowpath and the air flowpath, and the resulting periodic oscillations in the local fuel/air ratio can generate a positive feedback mechanism between heat release and naturally occurring acoustic modes. If the feedback mechanism is not damped, high dynamic pressure levels of only a few psi can result in damaged combustion hardware.

One method for minimizing the thermo-acoustic feedback mechanism is to design the premixer such that the pressure drop for fuel injection and for the combustor air inlet structures (liner holes or swirler vanes) are substantially matched (Black, 1993). Thus, dynamic pressure oscillations in the combustor have similar effect at both fuel and air flow inlet orifices, and the fuel/air ratio variations are mitigated.

While a premixer can be designed using this method for a single type of fuel, the dynamic benefits of the design will not hold true as the fuel is changed. As shown in Table 4, for a fixed fuel orifice area the fuel injection pressure drop, ΔPfuel, increases dramatically due to the higher fuel volumetric flow requirement as the LHV of the fuel is decreased. Thus, a single fuel injection circuit designed for natural gas will no longer have an acoustically matched design for any other fuel. In addition, fuel composition itself can cause changes in both pressure oscillation frequency and amplitude due to changes in the characteristic chemical reaction time – potentially augmenting or diminishing the flow rate-driven thermo-acoustic feedback mechanism. New fuel injection strategies must be considered that minimize the changes in the fuel injection pressure drop across the fuel space.

5.2.3 Aerodynamic Effects on the Combustor

Cycle calculations across the fuel space describe the effect on the combustor conditions and overall pressure drop as the heating value of the fuel changes. In general, the combustor pressure rises and combustor pressure drop decreases as fuel LHV decreases, due to the additional mass flow being injected into the combustor – mass flow that must pass through a turbine with a fixed inlet area and spinning at a constant speed. The actual method and location of fuel injection in the premixer can have additional effects on the aerodynamic conditions of the premixer itself.

One effect of high fuel flow rates in a premixer is increasing blockage of the air flow passages. This is particularly true if the fuel injection occurs at a location upstream of the major pressure drop in the premixer (for example, the swirler vanes) or a contraction in the premixer flow area. Introduction of increasing volumes of fuel will generate a reduction in the effective area of the air flow passages. Because air flow splits throughout a combustor are determined passively by the distribution of effective areas, large volumetric fuel flows may have the effect of shifting some air flow away from the premixer to all other areas of the combustor. For weak or high-inert fuels this effect may be advantageous, as it permits a higher fuel/air ratio (at a fixed fuel flow) in the premixer, enhancing flame stability. The opposite is true for highly reactive fuels, where typically a lower fuel/air ratio is desired to limit NOx emissions and is acceptable for flame stability. In fact, for high-H2 fuels, additional air flow through the premixer would be advantageous in order to stave off the propensity for flashback and flameholding.

Increasing fuel volumetric flows will also increase the premixer velocities, as shown in Table 4, although this effect will be somewhat diminished by the increase in operating pressure and decrease in premixer dP/P. Higher premixer velocities may affect the aerodynamic recirculation zone and thus flame stability, but will also improve the flashback resistance of the nozzle for high-reactivity fuels. Thus, a tradeoff and good design choices must be made between the premixer velocity impacts on flame stability, flashback resistance, and premixing efficiency/profile.

The combustion system depends on a complex distribution of air flows to feed various premixers, dilution holes, and cooling passages. Because of the potential effects noted above, flow network modeling must be performed to assess the impact of different premixer concepts on the combustor flow splits as a function of the fuel flow and load condition. Significant changes in the combustor effective area may also have an impact on the overall pressure drop of the combustion system; thus, the cycle modeling assumptions should be periodically assessed to track these potential effects.

5.3 Initial Fuel-Flexible Premixer Concepts

Wide fuel flexibility in a lean-premixed system poses a unique set of challenges in order to achieve broad operability and low emissions. The wide range of fuel volumetric flow rates can result in poorer performance on some fuels than others. Many strategies for mixing the fuel and air are closely dependent on fuel injection pressure ratio. As seen in Table 1, for a fixed geometry these pressure ratios will vary dramatically. Poor premixedness can result in high emissions, flame instabilities, flashback, and flameholding inside the premixer. In addition, fuel pressure ratio can also cause sensitivities to combustion dynamics.

The major premixer challenges to be addressed via this program are:

1. Fuel injection and premixing of a broad space of fuels with a wide range of volumetric flow rates
2. Stabilization of lean premixed flames burning weak and low-Btu fuels.

6 Emissions Entitlement Experiments and Model Development

One of the primary goals of lean premixed combustion technology is to minimize NOx emissions without the requirement for diluent. In a single-stage combustor, the path to minimum NOx at a given bulk average flame temperature is to perfectly premix the fuel. While perfect premixing may lead to lowest NOx, it is rarely achieved in modern combustors due to the challenges of premixing in very short distances and times. The desire for low NOx through premixing must also be balanced by risks of autoignition, aggressive fuel injection and diminished flameholding margin, maintaining burner velocities high enough to prevent flashback, flame stability challenges, and combustion dynamics. Even so, it is useful to perform experiments using perfectly premixed fuel/air mixtures in order to benchmark the best possible NOx emissions, termed the entitlement, and to provide validation data for detailed chemical kinetic modeling without the added complexity fuel/air mixing fluid dynamics.

Entitlement experiments were performed at GE Global Research in 1990 for natural gas fuel at elevated pressures (Leonard & Correa, 1990). This data has provided a benchmark for all DLN combustion systems to be compared against. For the present research program, experiments similar to the1990 tests were performed, but now extending the fuels and the condition space to match the DOE's fuels of interest.

6.1 High-Pressure Experimental Work

6.1.1 Entitlement Experimental Rig

Modifications were made to an existing experimental test rig in order to permit operation with the fuels of interest. The combustor section of the test apparatus is shown in Figure 10. The pressure vessel is capable of operation up to 300psig at 850F, and has windows for optical access to the combustor. The fuel mixture can be preheated in an electric heater up to 500F and mixed with air at temperatures up to 950F. Mixing occurs over a section of tubing with a length/diameter ratio > 200 inside the pressure vessel.

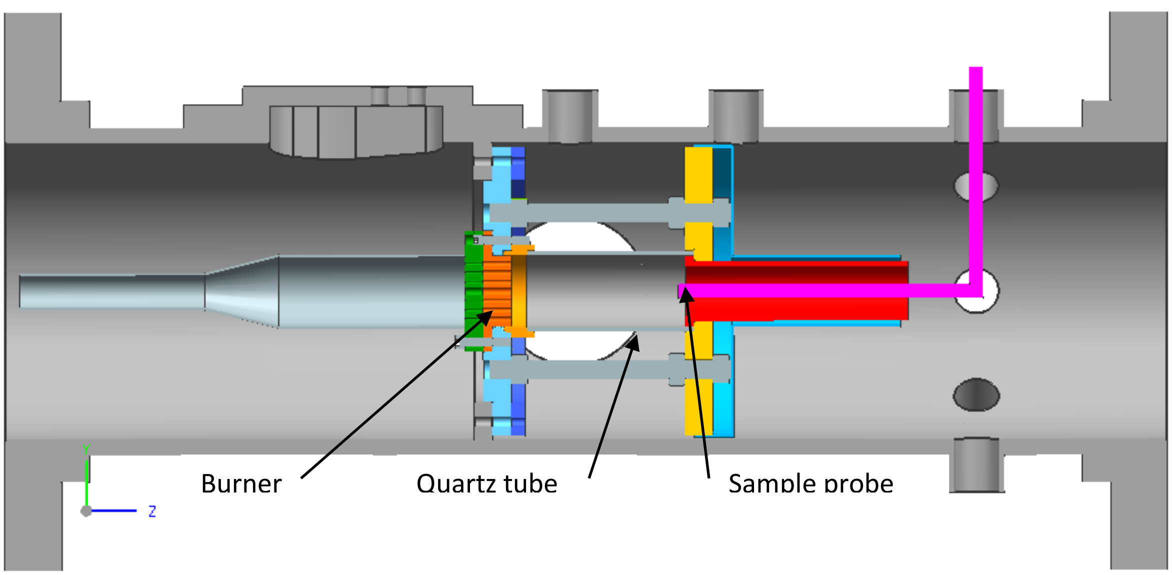

Figure 10: High-pressure entitlement experiments test rig.

6.2 Kinetic Modeling

Besides overall combustion efficiency, NOx and CO emissions are very important performance measures in the gas turbine industry. With trends and government emissions requirements continually decreasing, the design of low emissions combustors is increasingly important. Dry Low NOx (DLN) technology is utilized widely; however, lean combustion leads to flame stability issues. In particular, as the lean limit of the fuels is approached, NOx decreases but CO begins to increase. Accurate predictions of the behavior of NOx and CO within a combustion system are therefore very useful in the design phase of a combustor. Following the lean stability limit calculations presented in Section 5.1.2, NOx predictions were made using several modern chemical kinetics mechanisms and subsequently compared to recent NOx entitlement data. By comparing several mechanisms to the experimental data, it is possible to validate the NOx chemical kinetics. Depending on the performance of each mechanism, the most accurate mechanism can be down-selected and improved for future use.

Using the same chemical kinetic reactor network shown in Figure 8, several modern kinetic mechanisms were run at the experimental conditions. The GRI-Mech 3.0 mechanism (Smith, et al.) is often used as a standard in the combustion community and is well known for its methane combustion chemistry and NOx reaction scheme. Although this mechanism has been well studied, most of the validation has been conducted at lower pressures. These pressures are often lower than what is experienced in typical gas turbine combustors and therefore, more validation data are needed to ensure that the mechanism can accurately predict useful parameters such as lean blowout (LBO) and NOx emissions at high pressure. In addition, since the formulation of the GRI-Mech, there has been several other methane mechanisms published in the literature. Many of them have been validated against experiments at higher pressures and are therefore of interest to the current study. Two such mechanisms are (Petersen, Kalitan, Simmons, Bourque, Curran, & Simmie, 2007), noted here as the Galway mechanism, and the Kintech mechanism. It is important to note here that the Galway mechanism, as published, does not contain a NOx subset of reactions. Therefore, a NOx reaction scheme from another recent mechanism, from (Ranzi, Dente, Goldaniga, Bozzano, & Faravelli, 2001), has been inserted into the Galway Mechanism, which will hereafter be referred to as the Modified Galway Mechanism. In addition, the Kintech Mechanism has been developed through collaboration between GE Global Research and Kintech Corporation (Russia) over the past two years. The basis of the mechanism is the GRI-Mech 3.0; with modifications and reaction rate updates intended to improve its predictive capability at the high pressure, low temperature conditions in the premixed fuel-air flow where a plasma would operate for lean flame stability enhancement.

6.3 CFD Modeling

The role of CFD modeling is to support concept evaluation, comparison and optimization. Since predictive capability of CFD for opportunity fuels of interest has not been studied carefully, the first step is to assess CFD modeling capability for the desired application. Initial assessments of CFD to predict combustion characteristic trends for premixed natural gas at varying stoichiometric ratios are presented here. CFD predictions are compared with entitlement experiments for fully premixed fuels.

6.3.1 CFD Simulation Details

Figure 11 shows the entitlement experiment geometry used to define the computational domain in the CFD. The geometry consists on an inlet chamber followed by flame arrestor tubes leading into the combustion chamber. An outlet chamber follows the combustion chamber. An emissions sampling probe is placed immediately at the exit of the combustion chamber to measure species concentrations.

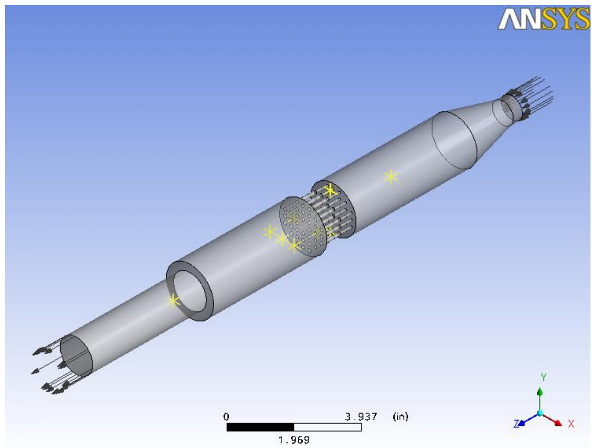

Figure 11: Geometry of entitlement experiment used in the CFD simulation. Flow is from right to left.

A tetrahedral mesh with 3.1 million cells and 605,000 nodes was created using CFX Mesh. This grid was further improved to remove cells with skewness greater than 0.8 using TGrid and Fluent smoothing algorithms. Cell-height near wall was chosen such that the height in near-wall non-dimensional units was less than 200. All CFD simulations were performed in Fluent 6. Steady Reynolds-averaged Navier-Stokes (RANS) equations with standard wall functions were solved. Due to low velocities in the combustion chamber and high velocities in the flame arrestor tube, a low Reynolds number correction was required to damp the turbulence eddy viscosity. Hence, the transitional k-ω model was chosen to model the turbulence with transitional effects.

Reactions were modeled using the partially premixed model. Additional equations for the reaction progress variable, mixture fraction mean and variance are solved. Since the flow is premixed, the mixture fraction is 1.0 at all spatial locations and time. The reaction progress variable is 0 where the mixture is unburned and 1 where the mixture is burned. The power of the mixture fraction modeling approach is that the chemistry is reduced to solution of one conserved variable. Under the assumption of chemical equilibrium for the burned mixture, all thermo-chemical scalars (species fractions, density, and temperature) are uniquely related to the mixture fraction. Only 16 species were included in the chemical equilibrium assumption for natural gas because the slow-forming nitrogen-related species were removed. The flow was assumed to be non-adiabatic and an enthalpy equation is solved. A flame stretch model needs to be activated for premixed fuel-air mixtures near lean blow-off. The reaction source term is multiplied by a stretch factor that represents the probability that flame is locally not quenched. To compute the stretch factor, a critical rate of strain is specified. Assuming a log-normal distribution for the turbulence dissipation, the flame is locally quenched if the dissipation exceeds the critical value. Based on Fluent recommendations for natural gas, the critical rate of strain is taken to be 8000 /sec. The partially premixed model also requires the specification of laminar flame speed that is obtained from detailed chemical kinetics calculations discussed above. Thermal NOx formation is computed in a post-processing step assuming partial equilibrium of [O] and [OH] species.

In summary, for both natural gas and syngas fuels, the CFD calculations initially predict a lifted flame when the burner tube velocities are high and a low value for the critical stretch parameter is applied. The higher flow rates produce high strains near the burner plate tubes, causing the flame to be locally extinguished. As demonstrated in preceding section, the flame shape and stability of the flame (lift-off) is highly sensitive to the choice of the critical flame stretch parameter.

We believe at this time that the experimental flame shape could be "fit" to some degree through the adjustment of this stretch parameter in the CFD model. The correct choice of stretch parameter is strongly geometry and flow dependent, but may also have dependence on the fuel characteristics. Once this parameter is adjusted to produce a better representation of the experimental flame shape, the calculated NOx could be more robustly compared to the experimental data and the detailed kinetic predictions. While this comparison is of interest, ultimately in this research program the CFD is to be used as a tool for evaluating premixing fuel nozzles – primarily swirl-stabilized premixers.

7 Fuel Flexible Premixer Evaluation

Key criteria for evaluating fuel-flexible premixer concepts were previously highlighted in Table 7. The major premixer challenges to be addressed via this program are:

- Fuel injection and premixing of a broad space of fuels with a wide range of volumetric flow rates
- Stabilization of lean premixed flames burning weak and low-Btu fuels.

Across the fuel space, a fuel-flexible premixer design must balance:

1) Fuel injection pressure requirement (facilities limitations)
2) Premixing efficiency (emissions targets)
3) Flame stability (operability range, dynamics)
4) Controls requirement (variability from 100% NG to 100% opp. fuel)

7.1 Initial Concept Evaluation – Balancing Pressure Drops

In section 4.1 we have described the impact of wide fuel flexibility on the gas turbine cycle conditions. Specifically, cycle deck calculations have been performed for the MS6000B gas turbine, resulting in values for temperatures, pressures, and pressure drops across the load range for premixed operation. For the various target fuels of this study, the combustor conditions (particularly total pressure drop) can vary significantly. The cycle deck primarily focuses on the impact on the air flow conditions.

7.2 Experimental Evaluation of Premixer Concepts

7.2.1 Bench Scale Atmospheric Experimental Setup

An existing experimental facility was modified and re-commissioned for the evaluation of a series of subscale fuel-flexible premixer concepts at atmospheric pressure. Data from this experimental setup was utilized to evaluate the performance of different premixer designs, as well as to provide data for validation of combustion and fluid dynamic models.

The experimental setup is depicted in Figure 12 and in a cross section view in Figure 13. Preheated air enters the top of a plenum and flows vertically downward through the rig. The flow is diffused at the top of the plenum with a perforated plate to provide uniform flow upstream of the fuel nozzle. The fuel/air premixer is mounted to a flange at the bottom of the plenum and is fully contained within the plenum. The flange incorporates a removable adapter ring to provide flexibility for mounting different nozzle designs. The plenum is split into two sections, allowing it to be separated in order to access the premixer and instrumentation. Fuel lines are fed through the plenum wall adjacent to the premixer, keeping the lines short to limit unwanted fuel preheating. (The fuel gases pick up varying amounts of latent heat from the fuel piping inside the plenum, depending on the fuel volumetric flow rates. A thermocouple is located inside the fuel lines at the location of the premixer to monitor the fuel temperature just before entering the premixer.) A hydrogen torch mounted through the premixer flange is used for igniting the combustible mixture.

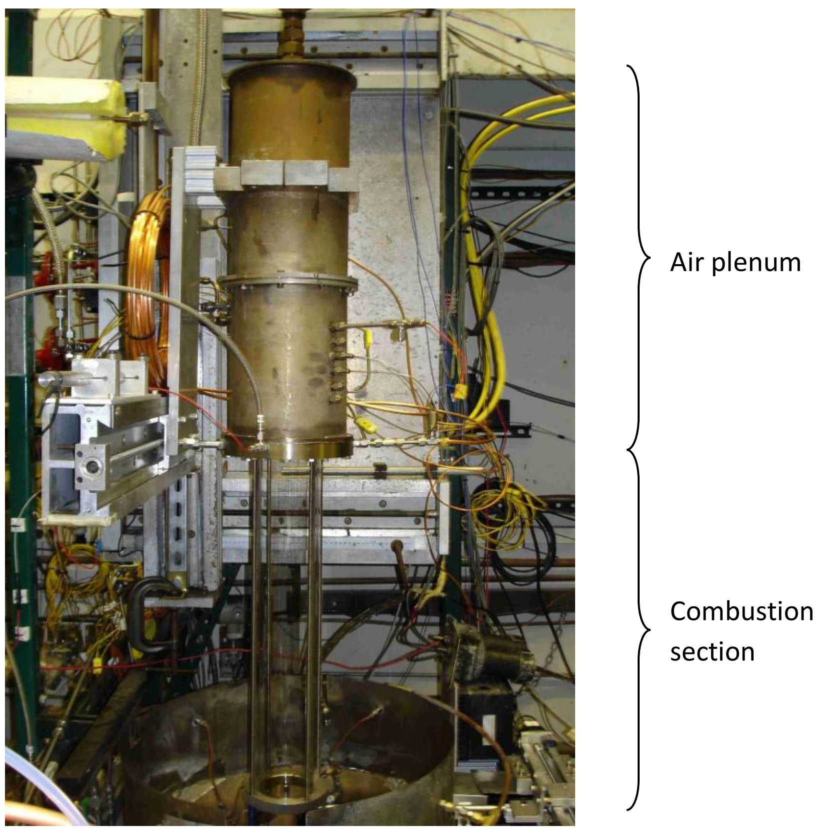

Figure 12: Experimental combustion test facility for 1 atm premixer concept evaluation.

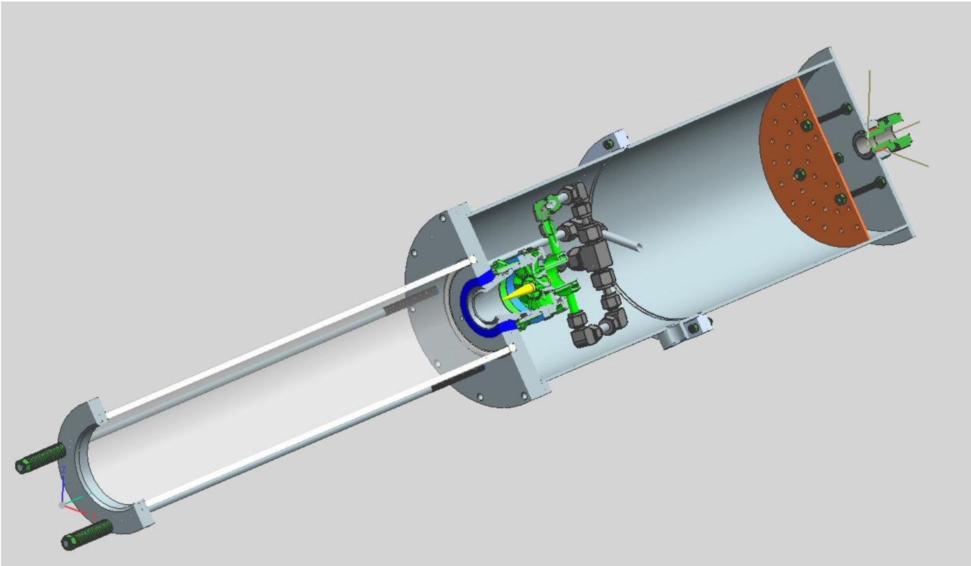

Figure 13: Cross section of experimental rig, depicting one concept premixer and the internal piping of the air plenum. The combustor exit conical reducer is not shown in this figure.

The fuel-air flow exits the premixer into a 4” diameter x 24” long quartz tube combustion section, which permits visual access to the flame. The combustor size is designed to yield nominal residence times of ~20ms, which will vary depending on the fuel type and the flame temperature. For non-combustion premixing tests, the 24” tube is replaced with an 8” long tube to permit easier access to the premixer while still retaining the same expansion ratio from the nozzle to the combustor. The bottom of the combustor is supported by a stainless steel ring, and a conical reducer slightly accelerates the flow at the exit. Combustion gases exit the combustor, are cooled by a water spray quench and drawn out of the room via an exhaust system.

A variety of instrumentation is used to characterize the premixer performance. Thermocouples, pressure transducers, and differential pressure transducers measure temperatures and pressure drops inside the plenum, premixer, and combustor. This instrumentation is fed through the plenum wall or the premixer flange. Locations for the instrumented points are shown in Figure 14. A piezo-electric pressure transducer is mounted through the premixer flange to measure combustor dynamic pressures.

The emissions sampling system is a key piece of instrumentation for our laboratory, and plays a critical role in the evaluation of the premixer concepts for this research program. The gas analyzers and flow controls are shown in Figure 15. Analyzers include measurements of NO/NOx, CO and CO2, CH4 and O2, and a second CO2 analyzer. The cooled sample is collected continuously using a diaphragm pump, after which it is dried and filtered in a Universal Analyzers sample cooler and passed to the flow controls for the bank of analyzers. Two different sample probes are used for species concentration measurements. In premixing measurements (non-combustion), a 1/8” diameter stainless steel probe is used to sample the gas concentrations at the exit plane of the premixer. This probe is depicted in Figure 14. Sample flow rates are kept low, yielding an effective probe diameter of 0.070[in]. (For reference, the premixing nozzle exit diameters are on the order of 1.4[in].) For combustion experiments, a water-cooled stainless steel sample probe is inserted approximately 1.5[in] upstream of the reducer cone exit plane. Both sample probes are mounted on a 2-axis programmable translation stage, permitting X- and Y-axis profile scans of the gas flows.

The combustion test was supplied with the 4 target fuels (natural gas, high-inert natural gas with 60% N2, and two different syngas blends) from our natural gas compressors and gas mixture bottle packs. In addition, natural gas was blended with any of the bottle fuels from 0 to 100% blend fraction. In addition, a pilot fuel circuit can also be utilized if needed in the various nozzle concepts. Data is collected via a combination of slow and high-speed data acquisition hardware and software in a LabWindows environment.

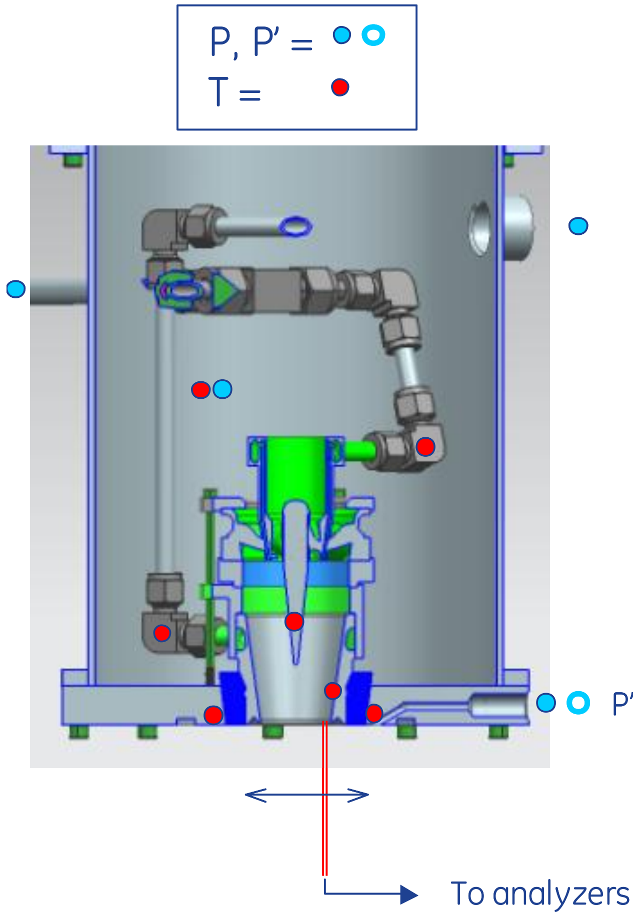

Figure 14: Instrumentation points inside the air plenum and premixer. Red circles represent temperature measurements and blue circles represent P or dP measurements.

Figure 15: Test cell emissions sampling system.

7.2.2 Fuel-Air Premixing Test Setup

The first experiments performed on each concept premixer are measurements of the premixing profile and overall premixedness of the nozzle. The objective of these tests is to provide data for comparison against CFD models and for building transfer functions between premixedness and combustion performance, specifically flame stability and emissions. Premixing tests are designed to mimic as closely as possible the conditions of the eventual combustion test. Surrogate “fuel” gas mixtures are used instead of the actual fuel gases. This method enabled longer duration testing without the dangers of exhausting unburned fuels and the wasting of expensive fuel blends. Four different surrogate inert gas mixtures are designed to match the molecular weight of each of the actual fuels, thus providing the same fuel injection behavior (mass flow rate, volume flow rate, and momentum ratios) as the fuel gas. The mixture is tailored to provide both low uncertainties in the species concentration measurements as well as flexibility to create blends that represent the entire fuel space.

For this work, a 70% N2 / 30% CO2 blend was mixed in varying ratios with 100% helium to simulate the entire fuel space. The key species measured were CO2 and O2 mole fractions using standard near-IR and paramagnetic gas analyzers, respectively. Table 6 shows the gas blends used to represent the various fuels of interest, with an estimation of the ideal uncertainty in the fuel mole fraction shown in the last column. Depending on the uncertainties in the purchased CO2/N2 blend, uncertainties in gas flow rates, and available analyzer ranges, measurements of CO2 and/or O2 may alternatively be used to characterize the premixer performance. CO2 is typically the most sensitive species due to its high dynamic range within the premixing flow. It is also measured when we sample directly the fuel flow prior to entering the premixer to verify the surrogate fuel blend. However, CO_2 mole fraction in the fuel/air mixture (and therefore the resulting premixedness data) is very sensitive to uncertainties in the CO_2/N_2 blend and fuel flow rate measurements of the 2 gas components. Oxygen measurements are much less sensitive to fuel blend uncertainties; however, they may yield large premixedness uncertainties in when fuel flows are small and the dynamic range of O_2 concentration across the premixer is very limited. Fundamentally, both measurements yield the same qualitative mixing profile measurements with different levels of uncertainty in the quantitative value.

Table 6: Surrogate gas blends for premixing measurements.

								(70% N2 / 30%CO2) + He			
Fuel	**Gas**	**Mole Fraction**	**Mass Fraction**	**Wobbe Index (MWI)**	**Mol Wt**	**F/A, mass**	**F/A, vol**	**X_CO2, Fuel**	**X_CO2, Premix**	**uX_Fuel, Premix**	**% of value**
100% NaturalGas	NatGas	1.000	1.000	52.53	16.719	0.032	0.055	0.1324	0.0069	0.0020	**3.7**
40/60 NatGas/N2	NatGas	0.400	0.276	17.7	23.225	0.129	0.160	0.2002	0.0276	0.0015	**1.1**
	N_2	0.600	0.724								
Medium BTU Syngas	CH_4	0.030	0.021	11.74	22.493	0.210	0.269	0.1925	0.0409	0.0019	**0.9**
	N_2	0.040	0.050								
	CO	0.360	0.448								
	H_2	0.340	0.030								
	CO_2	0.230	0.450								
Low BTU Syngas	CH_4	0.065	0.040	7.24	26.154	0.450	0.496	0.2307	0.0765	0.0021	**0.6**
	N_2	0.450	0.482								
	CO	0.185	0.198								
	H_2	0.140	0.011								
	CO_2	0.160	0.269								

7.2.3 Conclusions and down select

Based on the analyses and subscale concept data, the primary fuel-flexible premixer concept being down selected for further development is the WWDLE_2 design. Overall, the WWDLE_2 concept (including benefits from co-rotating swirler) highlighted the most promise for consistent operation on a continuously variable composition fuel stream, demonstrating low NOx and manageable pressure ratios over a very wide range of fuels. Improved mixing design should yield a positive impact across the fuel space. The second concept downselected for further development is the multi-circuit nozzle design whose selection will be explored in detail in the next section. The multi circuit nozzle concept is an evolutionary design based on existing, robust gas turbine fuel nozzles currently optimized for a single fuel (natural gas). Development plans for this concept included the optimization of multiple fuel circuits to balance the key performance objectives: NOx (mixing), flameholding risk (syngas fuels), and dynamics sensitivity of fuel pressure ratios.

8 Premixer Scaling and Optimization

8.1 Flow Network Modeling

In the earlier phase of this study, GE MS6000B ("6B") gas turbine engine was chosen as the target platform for new fuel-flexible premixer development. This engine incorporates a lean-premixed (Dry-Low NOx, or DLN-1) combustion system which has already demonstrated significant fuel flexibility in laboratory research and has the best potential for successful operation on the very broad fuel targets of this program. To evaluate the machine's ability to operate across all target fuels, cycle models were previously exercised and the impact on the temperatures and pressures in the combustor as well as overall machine parameters were assessed. While this model verified overall cycle conditions and operability, it does not provide detailed information about the impact of fuel flows within the combustor. Because the fuel-to-air ratio in this program varies over a factor of 10x from natural gas to syngas, the effects of large fuel flows on the combustor must be considered – especially as it impacts premixer design and operating conditions.

8.2 Multi-Circuit Nozzle

One route to wider fuel flexibility in a fuel/air premixer is to add additional fuel circuits. Fuel injector sizing must typically be optimized around one design point and a particular fuel. Because the premixing and combustion process can be sensitive to fuel pressure ratio and fuel jet penetration, lean premixed combustion systems often incur narrow limits on the acceptable fuel composition (typically +/- 5% in Modified Wobbe Index, or MWI). One solution is to design a nozzle with more than one fuel circuit, in order to accommodate more than a single fuel design point (GE Disclosure #20717). This design enables the nozzle to achieve fuel flexibility across both the individual target fuels of this program, as well as variable blends of opportunity fuels with standard natural gas.

8.3 WWDLE_2 Scaling and Optimization

8.3.1 WWDLE_2 Premixer Scaling

The Wide Wobbe DLE_2 premixer concept was downselected as the second fuel flexible premixer concept for high pressure evaluation. Based on experimental data at 1atm and CFD results a new next generation nozzle design of the WWDLE_2_co was scaled-up for full scale and high-pressure testing. The WWDLE-X concept incorporates unique design features with the intent of achieving consistent premixing and fuel pressure ratio across a broad fuel space. Such capability has the potential to open up the acceptable fuel variability in a given design, as small to large changes in fuel Wobbe index do not strongly influence the premixing process and the fuel pressure drop. The new design has also the intermediate tapered premixing section in order to maintain the center recirculation region that anchors an M-shaped flame. Special focus was placed on improving NOx emissions from the high temperature center recirculation region while maintaining the flame shape.

8.3.2 CFD Simulations and Optimization

8.3.2.1 Impact of Combustion Model

To evaluate the impact of turbulence models on the CFD predictions of premixing and flow field, large eddy simulations (LES) of the WWDLE_2_co with the tapered centerbody were performed. As shown in Figure 16, a tetrahedral mesh with about 10 million CFD cells was created using ICEM CFD mesher. The maximum cell skewness is 0.79, the maximum cell squish is 0.77, and the maximum aspect ratio is 17.6. The 1/5th sector CFD geometry includes the air and fuel inlets, the premixing nozzle with the straight premixing section (shown in the dashed circle), a sudden expansion into the combustor volume, and a reducer at the end of the combustor. The air enters through the inlet section (depicted in blue) and is swirled in the same directions in the inner and outer passages of the nozzle. The fuel enters through a separate inlet (depicted in red) and passes through a fuel passage located between the inner and outer swirlers. In the LES calculations, the Smagorinsky-Lilly model with enhanced wall treatment and dynamic stress is used to model the flow field. The partially premixed combustion model in Fluent with the dynamic scalar flux is used to model the premixing of fuel and air streams. Transport equations for the mean and variance of mixture fraction are solved to predict the mixing. For the non-reacting simulation, the transport equation for the reaction progress variable is not solved. Mass flow rates of the different components are specified at the inlet boundaries and the velocity is assumed to be normal to the specified boundary. At the exit, static pressure is specified. Second order schemes are used for both space and time. Details of the boundary conditions for the 100% Natural gas are tabulated in Table 7.

Figure 16: LES Mesh of the 1/5th sector CFD simulation with enforced rotational periodicity.

Table 7: Details of representative fuels and boundary conditions chosen for premixing study

	Natural Gas	**Low Btu Syngas**
Air mass flow rate (lbm/sec)	0.1008	0.0997
Total temperature @ air inlet (F)	591.4	576.6
Fuel mass flow rate (lbm/sec)	0.00334	0.0440
Total temperature @ fuel inlet (F)	292.98	79.34
Reference Static pressure (psia)	14.698	14.698
CH_4 mass fraction in fuel	0.900	0.040
C_2H_6 mass fraction in fuel	0.057	0
N_2 mass fraction in fuel	0.044	0.482
CO_2 mass fraction in fuel	0	0.269
CO mass fraction in fuel	0	0.198
H_2 mass fraction in fuel	0	0.010

To quantify the mixing process in the premixer, the evolution of unmixedness along the axial direction is studied. For the 100% natural gas case, $\tilde{\tilde{\xi}} = 0.032088$; and for the Low Btu Syngas case, $\tilde{\tilde{\xi}} = 0.3061034$. This standard definition indicates how far local mixture deviates from the perfect mixing state.

As opposed to the minor differences in Unmixedness and mixing profile when using different RANS turbulence models compared to LES, the choice of modeling method has a dramatic impact on the prediction of a vortex breakdown region and ultimately the flame shape. In stark contrast to the RANS prediction, LES predicted a center recirculation zone. However, as discussed in the following section, the experimentally observed flame shape appeared to be much more closely represented by the existence of a center recirculation zone.

In addition to the partially premixed combustion model, we also evaluate the laminar finite rate (LFR) combustion model under the species transport category, in which finite rate chemistry can be incorporated. With the LFR model, for each chemical species Fluent solves its species conservation equations, describing its convection, diffusion, and reaction sources. The k^{th} Reynolds averaged species mass fraction transport equation is

$$\frac{\partial}{\partial t}\left(\bar{\rho}\bar{Y}_k\right)\frac{\partial}{\partial x_i}\left(\bar{\rho}\bar{u}_i\bar{Y}_k\right) + \frac{\partial}{\partial x_i}\left(\overline{\rho u''_i Y''_k}\right) = \frac{\partial}{\partial x_i}\left(\overline{\rho D_k}\frac{\partial \bar{Y}_k}{\partial x_i}\right) + \bar{R}_k \tag{11}$$

where the terms on the left are the unsteady term, the convection by the mean velocity and the convection by turbulent velocity fluctuations; and the terms on the right are the molecular diffusion and mean chemical source term, respectively. In general, the turbulent flux term is modeled by mean gradient diffusion as $\overline{\rho u''_i Y''_k} = \mu_t / Sc_t \cdot \partial \bar{Y}_k / \partial x_i$, where μ_t and Sc_t are turbulent viscosity and turbulent Schmidt number, respectively. For LFR, the mean reaction source is modeled as $\bar{R}_k = R_k(\bar{Y}, \bar{T})$, i.e., the mean reaction rate is computed as the reaction rate evaluated at the mean composition. Therefore, the laminar finite rate model does not account for the turbulence-chemistry interaction.

In the reacting calculations with LFR, the realizable k-ε turbulence model with enhanced wall functions is used to model the flow turbulence. The chemistry mechanism used is DRM22, which contains 23 species and 102 elementary reactions. It is a skeletal mechanism developed from GRI1.2 for methane, and its validations are available at http://www.me.berkeley.edu/drm/. Hence in the Fluent calculation, in addition to the momentum, turbulence and energy equation, Fluent also solves the transport equations for the 23 chemical species. To alleviate the computational cost associated with the use of detailed chemistry, the ISAT tabulation method with an error tolerance 2x10-4 is used to speed the chemistry calculation. The boundary conditions are listed in Table 7. With the laminar finite rate model, a burning Bunsen-shape flame is predicted. In contrast, the partially premixed model did not predict a burning flame for this case.

With the laminar finite rate model and the detailed mechanism DRM22, burning solutions are predicted along with detailed information of temperature and chemical species. This provides a necessary prerequisite to meaningful NOx predictions. In this study, the FLUENT NOx model is used to predict the NOx emission in the WWDLE_2_co premixer. The Fluent NOx model is a post-processing operation, which solves the transport equation of the NOx species with fixed flow, temperature and all other chemical species. The FLUENT NOx model accounts for both the thermal NOx and prompt NOx mechanisms.

The predicted NOx15 at the combustor outlet is 2.85ppm, which is somewhat close to the experimental measurement of 3.7ppm. The contours of the rate of NO formation along with temperature and CO concentrations reveal that NO is formed in the flame front region, and the thermal NOx is the dominant cause of NO formation. The predicted CO15 at outlet is 28ppm, and compares reasonably well to the experimentally measured value of 20ppm for this nozzle and 2800F flame temperature. Note that these comparisons must be treated with caution, as the heat losses in the experimental apparatus are not accounted for in the model (which assumes adiabatic conditions).

8.3.2.2 Impact of Centerbody

Large eddy simulations of a two different centerbody designs with varying convergence angles were performed to ascertain its impact on premixing and flow field. Comparisons between the two designs of premixing sections are made to identify the effect of the shape of the premixing section on premixing, swirl number, flame shape, and emissions. Without changing the swirlers or fuel injection geometry, the straight premixing section is anticipated to achieve similar mixing and improved swirl number, therefore producing a stronger vortex breakdown and recirculation zone.

A tetrahedral mesh with 5.34 million CFD cells was created using ICEM CFD mesher. The maximum cell skewness was 0.8. The grid sensitivity study performed in the previous report ensures that the obtained CFD results are numerically accurate. Steady Reynolds-averaged Navier-Stokes (RANS) simulations were performed using ANSYS Fluent. Realizable k-ε turbulence model with enhanced wall functions is used to model the flow turbulence. The partially premixed combustion model in Fluent with the turbulent Schmidt number 0.4 is used to model the premixing of fuel and air streams. Transport equations for the mean and variance of mixture fraction are solved to predict this mixing. Both non-reacting and reacting simulations were performed. For the non-reacting cases, the transport equation for the reaction progress variable is not solved. Mass flow rates of the different components are specified at the inlet boundaries and the velocity is assumed to be normal to the specified boundary. At the exit, static pressure is specified.

Two fuel compositions that span the range of opportunity fuels of interest are chosen for the CFD premixing study: the 100% natural gas and Low Btu Syngas. The boundary conditions are chosen to match the experiments conducted in the atmospheric-pressure rig. The inlet airflow rate is held nearly fixed for the different fuels. The stoichiometric ratio of the different fuels is chosen to provide roughly the same effective adiabatic flame temperature.

A detailed examination of the contours of mixture fraction reveals that the straight section design has a more uniform mixing in the inner radius region (particularly for the LBTU case) due to the recirculation zone after the tip of the nozzle, but has no significant impact on mixing in the outer radius region. Without any changes in the fuel injection geometry, it is clear that the bluff centerbody in the straight design will generate a hub-rich profile, which is likely to give both strong flame stabilization as well as potentially higher NOx emissions due to the higher fuel/air mixtures and therefore flame temperatures in this stabilization region.

The improvement in the swirl number and the creation of a strong center recirculation zone is likely to improve flame stabilization. The net effect on the nozzle will be to improve the Lean Blow-Out (LBO) limits for the nozzle, decreasing the flame temperature at which a stable flame will operate. The negative impact will be potentially higher heat transfer to the centerbody tip, requiring some additional cooling flow to maintain material durability.

Reacting flow simulations for the WWDLE_2_co nozzle with straight premixing section was performed using natural gas. Combustion is modeled using both the partially premixed model and the laminar finite rate (LFR) model. The partially premixed model in Fluent combines the Zimont premixed combustion model and the laminar flamelet non-premixed combustion model. In addition to mixture fraction mean and variance, the governing equation for the reaction progress variable is also solved in the reacting calculation. The reaction progress variable indicates the combustion progress with zero representing that the mixture is unburned and one representing that the mixture is fully burned. In Fluent, the flamelet calculations are preprocessed and stored in look-up tables to reduce computational costs. The GRI-Mech 3.0 kinetic mechanism is used to generate the laminar flamelets.

In the LFR model, for each chemical species Fluent solves its species conservation equations, describing its convection, diffusion, and reaction sources. In the reacting calculations with LFR, the chemistry mechanism used is DRM22, which contains 23 species and 102 elementary reactions. Details of the boundary conditions are tabulated in Table 7. The axial velocity contours confirmed that vortex breakdown does occur, thereby generating a center recirculation zone that anchors the flame. The reaction progress variable contours indicated that the flame is anchored in the center recirculation zone and its value is nearly 1.0 downstream of the flame, i.e., the mixture is fully burned.

8.3.2.3 Impact of Inner Swirler Vane Orientation

Figure 17 show the geometry of the co-rotating design used in the CFD study. A similar geometry file was employed for the analysis of the counter-rotating inner vane design. The 1/5th sector CFD geometry includes the air and fuel inlets, the premixing nozzle with the straight premixing section, a sudden expansion into the combustor volume, and a reducer at the end of the combustor. The air enters through the inlet and is swirled in the inner and outer passages of the nozzle. A small fraction (~2% by mass) of the total incoming air is purged through the center body for cooling purposes. The fuel enters through a separate inlet (depicted in red) and passes through a fuel passage located between the inner and outer swirlers. With the existing inlet holes in WWDLE-X, part of the airflow in the outer passage is entrained into the fuel passage depending on the fuel flow rate. The fuel-air mixture exits at the fuel injection post-orifice area between the inner and outer swirlers.

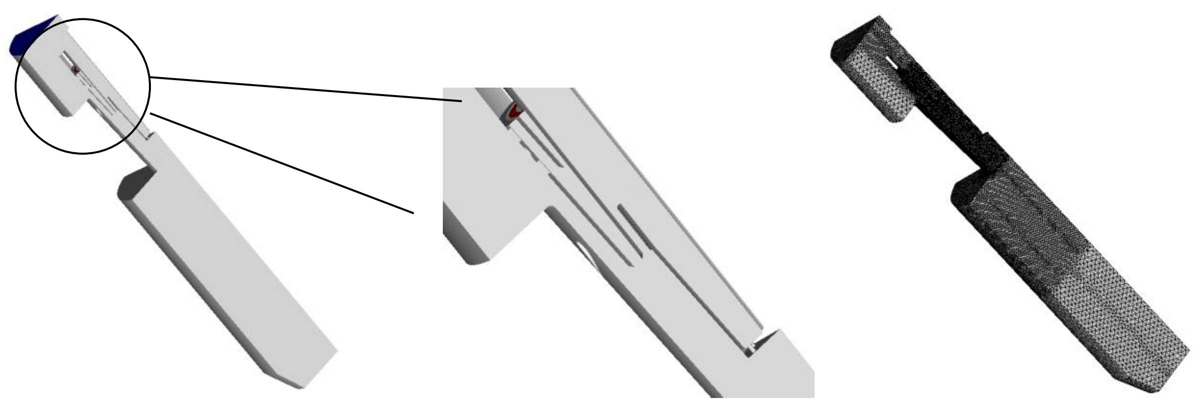

Figure 17: Geometry of the 1/5th sector CFD simulation with enforced rotational periodicity for the co-rotating design.

A hybrid tetrahedral/prism mesh with 5.9 million CFD cells was created using ICEM CFD mesher. The maximum cell skewness was 0.67, the maximum cell squish is 0.56, and the maximum aspect ratio is 10.6. Steady Reynolds-averaged Navier-Stokes (RANS) simulations were performed using ANSYS Fluent. The realizable k-e turbulence model with enhanced wall functions is used to model the flow turbulence. The laminar finite rate (LFR) combustion model in Fluent with the turbulent Schmidt number 0.4 is used to model the combustion process.

The chemistry mechanism used is ARM19, which contains 19 major species including NO and CO. It is a reduced mechanism developed from GRI2.11, which has 49 species and 277 elementary chemical reactions. In ARM19, the 30 minor species are assumed to be in quasi-steady state. With ARM19 no post-processing is needed to obtain NOx as it already contains NOx species. It also contains more elementary reactions and was developed from the more recent GRI2.11. ARM19 has been successfully used in the past both at GE and academia. Validations are available at http://www.sandia.gov/TNF/chemistry.html. Hence, in the Fluent calculations using ARM19, the transport equations for the major 19 chemical species are solved in addition to the momentum, turbulence, and energy equations. To alleviate the computational cost associated with the use of detailed chemistry, the ISAT tabulation method with an error tolerance 1x10-4 is used to speed the chemistry calculation. Mass flow rates of the different components are specified at the inlet boundaries and the velocity is assumed to be normal to the specified boundary. At the exit, static pressure is specified.

CFD calculations of the WWDLE-X premixer were performed with 100% natural gas and low-Btu syngas at three different adiabatic flame temperatures to study the impact on fuel/air mixing, flame stability and emissions. Details of the chosen cases and boundary conditions are tabulated in Table 8 and Table 9, respectively. The inlet airflow rate is fixed for the different fuels and different burner tube flame temperatures are achieved by adjusting the fuel mass flow rate. The fuel/air ratio of the different fuels is chosen to provide adiabatic flame temperatures of 2282°F, 2552°F and 2760°F for both the natural gas and the low-Btu case.

Table 8: Details of representative boundary conditions for 100% natural gas.

Air mass flow rate (lbm/sec)	4.064	4.064	4.064
Total temperature @ air inlet (F)	671	671	671
Fuel mass flow rate (lbm/sec)	0.0978	0.1174	0.1329
Total temperature @ fuel inlet (F)	60	60	60
Reference Static pressure (psia)	182	182	182
CH_4 mass fraction in fuel	0.900	0.900	0.900
C_2H_6 mass fraction in fuel	0.057	0.057	0.057
N_2 mass fraction in fuel	0.044	0.044	0.044
T_{Flame} Single Nozzle (F)	2282	2552	2760

Table 9: Details of representative boundary conditions for low-Btu syngas.

Air mass flow rate (lbm/sec)	3.771	3.771	3.771
Total temperature @ air inlet (F)	734	734	734
Fuel mass flow rate (lbm/sec)	1.054	1.3401	1.5977
Total temperature @ fuel inlet (F)	60	60	60
Reference Static pressure (psia)	200	200	200
CH_4 mass fraction in fuel	0.040	0.040	0.040
N_2 mass fraction in fuel	0.482	0.482	0.482
CO_2 mass fraction in fuel	0.269	0.269	0.269
CO mass fraction in fuel	0.198	0.198	0.198
H_2 mass fraction in fuel	0.010	0.010	0.010
T_{Flame} Single Nozzle (F)	**2282**	**2552**	**2760**

8.3.2.4 Summary

The impact of turbulence models on the CFD predictions of the premixing and flow field was studied by performing large eddy simulations (LES) of the WWDLE_2_co with a tapered premixing section. Compared to two different steady RANS models, LES predicts less mixing (a higher fuel/air ratio peak) in the inner radius region around 0.005m, and improved mixing (closer to the bulk average fuel/air ratio) in the outer radius region around 0.015m. Moreover LES predicts a peak fuel/air ratio location closer to the centerline. It is notable that the turbulence models seem to have negligible impact on the global mixing characteristic unmixedness parameter, Um, nor on the air split among different passages. In contrast to RANS predictions, LES calculations predict a center recirculation zone even for the tapered WWDLE_2_co design. This result would seem to be more in line with experimental observations, where the flame appears to expand and contain a lifted recirculation zone rather than the Bunsen flame shape predicted by the RANS models.

Through the non-reacting RANS simulation of the WWDLE_2_co with two different designs of the premixing section, it is observed that the change in the shape of the premixing section has no significant impact on the global unmixedness, U_m, or on the air flow split between different passages. However, the design with straight premixing section does dramatically increase the swirl numbers at the combustor inlet compared to the previous design with a tapered section. This improved swirl number is sufficient to induce vortex breakdown and produce a center recirculation region that can anchor the flame.

The impact of the combustion model on the CFD predictions of the reacting flows in WWDLE_2_co was also studied. For the tapered design, the laminar finite rate model predicts a burning Bunsen-shaped flame whereas the partially premixed model cannot predict a burning flame as shown in previous report. For the straight design, both the PPM and LFR predict an M-shaped flame anchored on the center recirculation zone. This M-shaped flame is quite different from the Bunsen-type flame in the WWDLE_2_co with tapered premixing section.

With the detailed information of temperature and chemical species available in the LFR model, the FLUENT NOx model was used to predict the NOx emission in the WWDLE2_co nozzle with tapered and straight sections. The calculations show both designs yield comparable CO emissions. However, due to the high temperature in the center recirculation zone, the design with straight premixing section is predicted to have significantly higher NOx emissions. For the tapered design, the predicted NOx15 at the combustor exit is in reasonably good agreement with the experimental measurements.

The effect of co-rotating and counter-rotating inner swirler vane designs on premixing, flame stability, and emissions has been studied. Steady RANS models were run for natural gas and low-Btu syngas. For natural gas, the model predicts good mixing of fuel and entrained air at the exit of the pre-chamber. For low-Btu syngas, however, poor fuel and air mixing is predicted at the pre-chamber exit. It is notable that the change of the inner swirl vane design has no significant impact on the global Unmixedness, U_m.

Reacting steady RANS simulations of the different WWDLE-X designs were also performed to evaluate the impact of inner swirl design on the flow field and flame stability. The results for co-rotating inner swirl vane design indicate a center recirculation region that anchor a M-shaped flame behind the tip of the center body for both natural gas and low-Btu syngas fuel. For the counter-rotating swirler design a recirculation region after the centerbody does not exist. The laminar finite rate model predicts a flame that is substantially pushed back downstream for natural gas and low-Btu syngas. For low-Btu syngas a Bunsen-shaped flame is predicted.

Emission predictions for the co-rotating designs show major NO production at the high temperature center recirculation region. For the counter-rotating swirl vane NO production is significant in the corner recirculation zone. The predictions indicate that there is little impact of the inner swirl vane design on NO emissions. CO predictions, however, show a dependency on the swirl vane design. With natural gas, an increase of CO emission was predicted for the counter-rotating design. It is caused by incomplete CO oxidization due to shorter residence times as the flame is stabilized further downstream.

Steady RANS models were run for different flame temperatures with natural gas and low-Btu syngas. For both fuels, the model predicts no significant impact of flame temperature on the good mixing of fuel and entrained air at the exit of the nozzle. The effect of flame temperature on the flow field and flame stability was also evaluated. The results indicate a center recirculation region that anchor an M-shaped flame behind the tip of the center body for both natural gas and low-Btu syngas fuel. While for the natural gas case the flame temperature had little impact on the flame position, for the low-Btu syngas the flame stabilization location moved upstream with temperature. The results show also as expected strong dependency of NO emissions on flame temperature.

CFD calculations of the WWDLE-X premixer were also performed for all four opportunity fuel of interest (natural gas, high-inert (60% N2) natural gas, medium-Btu syngas and low-Btu syngas) at an adiabatic flame temperature of 2760 °F. Similar mixing profiles were observed for the natural gas, high-inert (60% N2) natural gas and medium-Btu syngas. For the low-Btu syngas the mixing at the nozzle exit was predicted to be moderately better. For all the fuels, the results indicate a center recirculation region that anchor an M-shaped flame behind the tip of the center body due to the vortex breakdown where also the highest temperatures are found. For medium-Btu syngas a thinner and shorter flame front is observed compared to the other three fuels due to the higher hydrogen content and flame speed. For the low-Btu syngas, however, the flame is attached to the tip of the center body. Emissions predictions for all fuels show major NO production at the high temperature center recirculation region. Lowest NO emissions at the outlet are predicted for the low-Btu syngas. Vortex breakdown at the combustor inlet and flame stability are highlighted to be critical for successful operation of the concepts. To mitigate durability concerns, special emphasis was placed on optimization to prevent flashback/flameholding. Based on the above analysis, the co-rotating air swirlers and tapered centerbody features were incorporated for the final full scale WWDLE-X premixer.

9 High Pressure Fuel Flexible Premixer Evaluation

9.1 High Pressure Combustion Rig

The final objective of the DOE Fuel Flexible Premixer development program is the experimental evaluation of the down-selected premixer concepts under MS6001B (relevant gas turbine) pressure and temperature conditions across the fuel space of interest.

The full scale combustion experiments are performed in a high-pressure optically accessible single nozzle test rig highlighted in Figure 18. This rig has been previously employed for similar experimental studies and entailed some modifications for the needs of this research program. The detailed-design of the rig modifications were completed and all required internal parts have been manufactured and installed to facilitate the operation of the various fuel nozzles chosen for the current study. The experimental assembly consists of a front flange, upstream vessel, main vessel, mid-section, reducer and a back-pressure valve. The pressure vessels and flanges are ASME stamped and rated for operation up to 600 psia at 1000 °F. The front flange provides access for lines to transport fuel to the nozzle. Pre-heated and metered air from the compressor enters the upstream vessel. The upstream vessel substitutes as an air plenum, which facilitates the redistribution of the airflow into various components. The major portion of the air flows through the premixer into the combustor. A small fraction of the total air flows as cooling air via cooling holes located on the combustor upstream sections. The remaining air flows around the downstream section of the combustor to cool the liner. The nozzle, combustor and liner are anchored inside the main vessel. The main vessel has optically accessible ports, which provide visual access of the combustor section. Thermocouples, P and DP transducers are employed to monitor the flow properties inside the rig. The hot gas from the combustion chamber mixes with the liner cooling air in a mid-frame (not shown). The mid-frame also houses the sampling probes for emissions measurement. The total residence time in the test rig, from nozzle exit to emission sample probe, is approximately equivalent to the residence time up to the dilution section in the full combustor. A reducer facilitates the connection of the mid-frame to the exhaust pipe, which houses the back-pressure valve. The back-pressure valve is regulated to maintain the required pressure inside the combustion chamber.

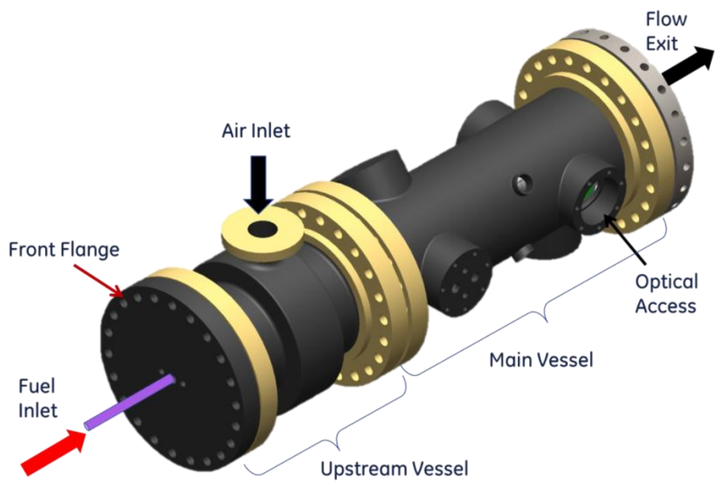

Figure 18: High-pressure single nozzle test rig for the experimental evaluation of the full-scale fuel flexible premixer concepts at gas turbine conditions.

Figure 19 shows the arrangement of the baseline MS6001B secondary fuel nozzle inside the high pressure vessel. The nozzle is held by a plate containing holes for air to pass through and is located at the combustor inlet. The nozzle exit and the heat shield (the front face of the combustor) are cooled with air from the upstream vessel to minimize hot spots from recirculation zones. Figure 20 highlights various combustor components on assembly. The exit of the nozzle is provided with a collar (containing impingement cooling holes) to shield the outer surface of the nozzle from hot products in the recirculation zone and also suffice to quench the combustor walls. Cooling air is also supplied via effusion cooling holes on the combustor walls. Figure 21 highlights various air flow paths inside the pressure vessel. The distribution of air among various components depends on the type and effective area of fuel nozzle being investigated. Table 10 lists the estimated air flow splits across various combustor components for the different fuel nozzles investigated in this study.

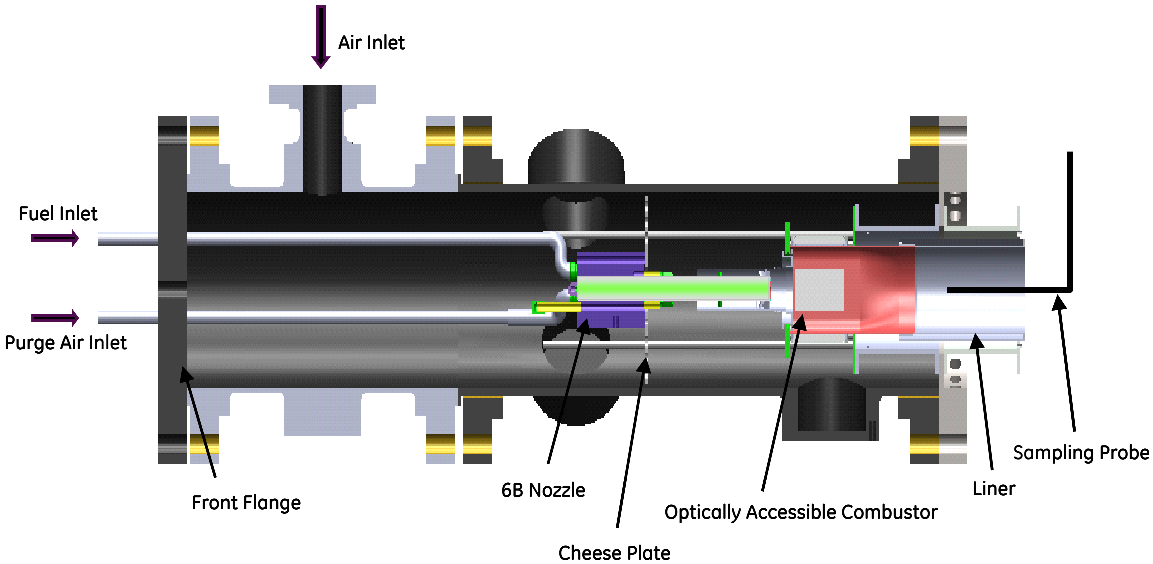

Figure 19: Cross-section view of the high-pressure single nozzle test rig.

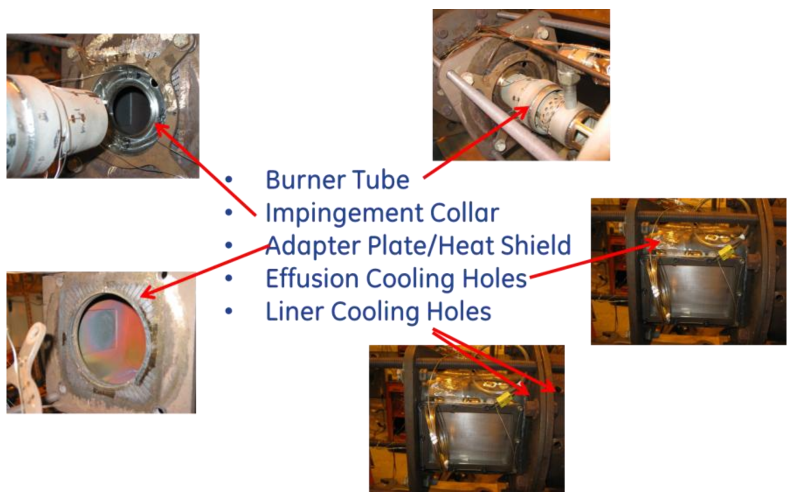

Figure 20: Components of the high-pressure single nozzle test rig.

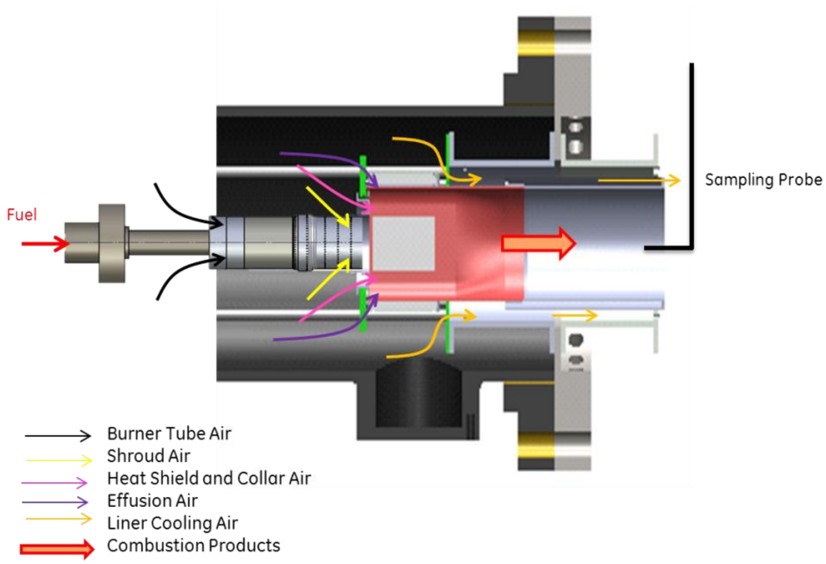

Figure 21: Cross-section view of the high-pressure single nozzle test rig.

Table 10: Air flow splits of various combustor components for the three fuel nozzles evaluated in this study.

Air Flow Splits (%)			
Concept	6B	MCN	WWDLE_2
Burner Tube Air	53.4	57.9	60.4
Shroud Air	7.7	3.7	0.0
Heat Shield and Collar Air	7.0	4.9	6.0
Effusion Air	6.6	4.7	5.6
Liner Cooling Air	24.3	28.7	28.0

9.2 Fuel-Flexible Premixers

The high pressure combustion experiments were undertaken with the multi-circuit nozzle, WWDLE-X and the baseline 6B DLN1+ secondary fuel nozzle at target MS6001B base load and part load conditions highlighted in Table 12.

9.3 Test procedures and instrumentation

Table 11 lists some of the important parameters of interest for the current study. Several of the critical parameters are measured indirectly such as the $T_{Combust\_O2}$. This quantity is estimated using the measured inlet temperatures and the exit O2 concentration to calculate post flame conditions assuming complete combustion and equilibrium conditions.

In section 9.4, we report results obtained with the multi-circuit nozzle, WWDLE-X and the baseline 6B DLN1+ secondary fuel nozzle at target MS6001B base load and part load conditions that are highlighted in Table 12. For each evaluated fuel composition, (100% natural gas and NG-60%N2 fuels) tests were conducted to obtain emissions, dynamics and lean blow off (LBO). Before each test, the gas analyzers were zeroed and spanned. The standard procedure for collecting steady state data calls for a steady head end temperature (T3), pressure (P3), and steady NOx values. Upon ignition, the flow values for burner tube velocity (BTV), combustion temperature, and combustion pressure (P4) are set by controlling the air mass flow, the fuel mass flow, and the test vessel's back pressure valves, respectively. Once the desired experiment conditions are reached and the temperature and NOx emission traces are stabilized, steady state data is recorded. The next test point is reached by adjusting the fuel and air flow rates at long enough intervals to allow ample time for the flow and measurement system to respond and equilibrate.

Emissions measurements were obtained using a water-cooled gas-sampling probe that is located downstream of the combustor as shown in Figure 19 and Figure 21. The extracted gases flow through heated lines to emissions analyzers where NOx, CO, CO2, O2, CH4, and unburned hydrocarbons species concentrations are continuously measured during the experiments. The target residence time for the flow from the exit of the nozzle to the probe is ~14ms at both baseload and part-load test conditions. Fuel mixture compositions estimated from measured fuel mass flow rates, pressure and temperature for the part load test conditions are listed in Table 13.

Table 11: Measured and calculated values of some important parameters in the current study.

Parameter	Measured	Calculated
T3 [°F]	TC upstream of nozzle	
P3 (psia)	Pressure transducer at head end	
P4 (psia)	Pressure transducer at combustor	
TFuel [°F]	TC upstream of nozzle on fuel line	
DPNozzle (psid)	Differential pressure transducer across the nozzle	
MFuel (lb/s)	Coiriolis flow meter	
MAir (lb/s)		From TOrifice, POrifice and pressure drop across orifice
Burner Tube Velocity, BTV (ft/s)		T3, P3, MAir, MFuel, annulus area between burner tube and centerbody, uniform flow
Nozzle Exit Velocity (ft/s)		TMix, MAir, MFuel, MPurge, nozzle exit area downstream of centerbody
TCombust_O2 [°F]		T3, P3, TFuel, Measured O2
NOx (15) (ppm)		Sampled NOx corrected by sampled O2 value
CO(15) (ppm)		Sampled CO corrected by sampled O2 value
Dynamics (psi, Hz)		Peak amplitude of 1 sec power spectrum

Table 12: High-pressure combustion test conditions corresponding to baseload and part load.

Baseload					
Parameter	Unit	NG	NG/N2	Mbtu	Lbtu
Pcd	psia	182	191	195	200
Tcd	F	671	687	694	734
Premixer Air Flow	lb/s	3.996	3.958	3.943	3.697
Tfuel	F	59	59	59	59
Max_Fuel Flow	lb/s	0.143	0.575	0.917	1.9
Min_Fuel Flow	lb/s	0.093	0.359	0.557	1.048
50% Load					
Parameter	Unit	NG	NG/N2	Mbtu	Lbtu
Pcd	psia	117	120	123	128
Tcd	F	603	619	625	657
Premixer Air Flow	lb/s	2.581	2.488	2.494	2.354
Tfuel	F	59	59	59	59
Max_Fuel Flow	lb/s	0.095	0.371	0.595	1.246
Min_Fuel Flow	lb/s	0.062	0.234	0.366	0.697

Table 13: Measured fuel mixture parameters of various opportunity fuels for part load conditions listed in **Table 3**.

Concept	Units	6B Baseline		MCN				WWDLE-X			
Fuel		NG	NG+N2	NG	NG+N2	Mbtu	Lbtu	NG	NG+N2	Mbtu	Lbtu
X_{NG}		1.00	0.39	1.00	0.41	0.05	0.08	1.00	0.39	0.07	0.06
X_{CO}						0.32	0.13			0.28	0.13
X_{CO2}						0.27	0.24			0.25	0.29
X_{H2}						0.36	0.16			0.40	0.21
X_{N2}			0.61		0.59	0.00	0.39		0.61	0.00	0.31
T_{Fuel}	F	94	67	109	86	99	80	93	68	87	80
MWI		51	17	50	18	12	7	51	17	13	7

9.4 High Pressure Testing Summary

In summary, the 6B baseline and the two downselected multi-circuit nozzle and WWDLE-X injector concepts were experimentally evaluated for their emission performance under gas turbine conditions with fuels comprising of natural gas, high-inert (60% N2) natural gas, medium-Btu syngas and low-Btu syngas. The 6B baseline nozzle was evaluated with natural gas and high-inert (60% N2) natural gas fuel mixtures only. The multi circuit nozzle was observed to exhibit low NOx for all the fuel mixtures of this study. For natural gas fuel, the NOx levels observed for the WWDLE-X concept were higher in comparison to the 6B baseline nozzle. The WWDLE-X concept exhibited CO benefits for natural gas. Single digit NOx are observed for syngas fuels for both MCN and WWDLE-X concepts. For low-Btu syngas, the NOx variations between the injector concepts were found to be less than ~1ppm.

In comparison to 6B and WWDLE-X concept, lower 1.peak amplitudes were observed for the multi circuit nozzle across all fuel space investigated in the study. On the other hand, higher amplitudes were observed for WWDLE-X. The 1.peak frequency behavior was observed to be identical for both the MCN and WWDLE-X concepts for low-Btu and medium-Btu fuels. For natural gas fuel operation, large variations in 1.peak frequency were observed between MCN and WWDLE-X. The dynamic amplitudes observed for MCN and WWDLE-X concepts are observed to be within the range of operability for current gas turbines.

The multi-circuit nozzle exhibited enhanced flame holding tolerance for medium-Btu fuel operation. No damage to hardware was observed even after the flame was intentionally held > 6 minutes in the burner tube. Flameholding tests conducted for the WWDLE-X premixer showed that the prechamber was flashback and flameholding resistant. Flameholding margins for the premixing region (burner tube) were established for low-Btu syngas operation. The downselected premixer concepts demonstrated enhanced reliability for sustained operation of opportunity fuels. The down-selected premixer concepts were successfully evaluated at target gas turbine conditions and demonstrated operability under wide fuel space (MWI from 7-50). The concepts also demonstrated single-digit NOx and favorable CO emissions over the opportunity fuel space of interest at wide range of gas turbine conditions. The fuel nozzle technologies have demonstrated clear benefits to both the mainstream and opportunity fuels based gas turbine market.

10 Commercialization Status

In Section 3, the current market needs were assessed based on customer fuel requests. It is clear from this assessment that 1) there are customer interests in and need for wider fuel flexibility in order to take full advantage of off-gas/byproduct streams in current and/or new gas turbine installations, and 2) the fuel space of interest is broad. Some fuel segments show more near-term potential than others. For example, gaseous fuels requiring no gasification or digestion are inherently easier to interchange with natural gas once the combustion technology has been developed. On the other hand, fuels requiring gasification involve additional levels of cost and risk to the industrial user, and the gasification technology may ultimately be the weak link in commercializing these fuels for gas turbines. The former group of fuels certainly has more near-term customer “pull” than the latter group. However, because of the high natural gas displacement potential of fuels like biomass, black liquor, pet coke, and municipal solid waste, and because the syngas produced from this group of feedstocks share overlapping traits with each other and with gasified coal, it is an important group of fuels for further advancements in combustion technology. The team will continue to push forward with the technical development program for fuel flexible combustion nozzles, while staying abreast of the market needs as determined by our commercial teams.

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Disclosures

The following Disclosures were initiated at various stages of the program:

- Disclosure #20717 “Combustor Fuel-Air Premixer with Multiple Fuel Circuits”
- Disclosure #20718 “Use of Fluidic Actuation to Create Reduced Nozzle Area via Virtual Aerodynamic Surface in Combustor Components”
- Disclosure #20719 “Active Variable Fuel Injection Geometry in a Gas Turbine”
- Disclosure #20720 “The Use of Porous Material for Flexible Fuel Injection”

- Disclosure #20723 “Imperfect Premixer for Weak Fuels”
- Disclosure #20724 “Plasma-Assisted Dry-Low Emissions/NOx Fuel Nozzle”
- Disclosure #20725 “Pulsed Power Plasma-Assisted Fuel Nozzle”
- Disclosure #20726 “Rich Plasma-Assisted Fuel Nozzle”
- Disclosure #20727 “Converging/Diverging Plasma-Assisted Fuel Nozzle”
- Disclosure #23373 has been converted to Docket #250219: “High Speed Low Loss Gate Drive Circuit”
- Disclosure #23372 has been converted to Docket #250271: “Solid State Pulsed Power Generator”
- Disclosure #20363, converted to Docket #242787 – “Passive air-fuel mixing prechamber to enable wide fuel-flexibility in gas turbine combustion systems” was filed as a patent application with the US Patent Office
- Disclosure # 35960 “Fuel Flexible Premixer for Gas Turbine Applications”