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ADVANCES IN USING ASSOCIATED GASES IN SOLAR® TURBINES' DLE INDUSTRIAL GAS TURBINES

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ABSTRACT

Industrial gas turbines equipped with conventional combustion systems have a well-established experience base operating on gaseous fuels from oil and gas production. Raw natural gas or gases "associated" with oil production are often flared. By using these gases to generate power for either compression, mechanical drive or electricity at the well head the amount of flaring is reduced. Regulatory and other business drivers by oil and gas companies are driving the use of gas turbines equipped with dry low emission (DLE) technology such as Solar's *SoLoNOx*™. In response to this interest Solar has developed and qualified gas turbine models with DLE technology capable of using this broad range of methane-based gaseous fuels. This paper describes what these fuels are and where they are used. Associated gases with Wobbe Index in the range of 18 to 60 MJ/Nm^3 have been studied. The fuel system and engine modifications and qualification processes to allow the use of these fuels in Solar's DLE engine models are discussed. The results of the development work are summarized in terms of gas turbine emissions and performance. Operational impacts of using these fuels are described and fuel treatment requirements are also highlighted. Finally, future development opportunities are also presented.

COMBUSTION SYSTEM DESCRIPTION

Solar uses two combustion system technologies in its gas turbines. A cross-section of the combustion system is included in Figure 1. The conventional combustion system uses diffusion flame combustion characterized by high flame temperatures and concurrent mixing and burning of the air and fuel within the combustor volume. Conventional combustion gas turbines exhibit excellent turn-down with very broad fuel flexibility.

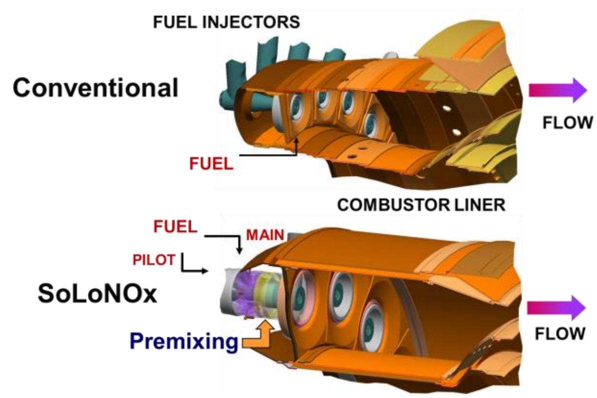

Figure 1. Comparison of Conventional and DLE (SoLoNOx) Combustion Systems

The other combustion system is Solar's DLE system, trademarked *SoLoNOx* that uses lean premixed combustion to operate with low emissions of NOx and CO. With lean premixed combustion, the fuel and air are premixed before reaching the flame front at a reduced fuel-air ratio and corresponding reduced flame temperature. A detailed description of the *SoLoNOx* combustion system and a comparison with the conventional fuel systems can be found in Cowell, 2002. Both the conventional and *SoLoNOx* configurations are available in either a single gas or with dual fuel capability in which both gas and liquid fuels can be used. Typically, in dual fuel applications a liquid fuel such as #2 Diesel is provided on generator applications to allow continuous operation in the event of an interruption in the gas supply.

ASSOCIATED GAS FUELS

Raw natural gas comes primarily from three types of wells: crude oil, gas and condensate. Natural gas that is extracted from crude oil wells is typically termed *associated* gas. Associated gas is found either dissolved in the oil or as a cap gas above the oil in the reservoir. This gas is most often produced offshore but can also be found in onshore oil recovery installations. Raw natural gas from either gas or condensate wells is typically termed *non-associated* gas since it will contain little or no crude oil. The fuel composition of either associated or non-associated gases varies by well. It is always rich in methane and includes other heavier hydrocarbons, primarily ethane, propane, and butane. These gases may also contain significant amounts of the diluents, carbon dioxide and/or nitrogen. Table 1 includes the composition of three typical associated gases from different classes based on heating value compared to a standard pipeline gas.

Historically, associated gas has been treated as a by-product of oil extraction and has either been flared or re-injected to extract more oil. Burning associated gas in the gas turbines used to extract the crude oil has been recognized as a more economical and

	Std NG	Associated Gases		
		Low	Med	High
Wobbe (MJ/Nm3)	43	19	29	55
Methane (%vol)	93	46	56	48
Ethane (%vol)	4	4	6	20
Propane (%vol)	1	2	4	16
Butane (%vol)	0.2	0.5	2	9
C5+ (%vol)	0.1	0.5	0.5	5
CO2 + N2 (%vol)	2	48	32	2
Dewpoint (C)	-37	6	19	68
Laminar Flame Speed (cm/sec)	121	83	107	135
Autoignition Time (msec)	124	88	81	64

Table 1. Typical Associated Gas Compositions

environmentally sensitive approach. The majority of associated gas is produced offshore, complicating further efforts to recover and utilize these gases. With proper precautions and handling, associated and non-associated raw natural gases are excellent gas turbine fuels.

The composition of associated gas depends on the type of reservoir from which it originated. The Wobbe Index range, calculated using LHV, varies from 18 to 60 MJ/Nm^3. The hydrocarbon dew point of these fuels also varies significantly depending on the composition. The presence of hydrocarbons heavier than methane results in higher dew point, faster laminar flame speed, and lower autoignition delay times as can be seen in Table 1. The laminar flame speed and autoignition delay time values listed are calculated using a commercially available code. More details about the numerical calculations are provided in the subsequent sections on autoignition delay times and flame speed.

With the advent of hydraulic fracturing and horizontal drilling natural gas extraction from shale formations has become economical. Shale gas may also be classified as a raw natural gas. It is close in composition to pipeline quality natural gas with a Wobbe

Index in the range of 35 to 46 MJ/Nm^3. Shale gas is also an excellent turbine fuel and generally defined as a standard natural gas fuel of pipeline quality.

Depending on the shale formation from where the gas is derived, shale gas may be “wet” with a mix of natural gas and Natural Gas Liquids (NGLs). In this case shale gas contains more ethane and propane than pipeline gas, which has to be reduced prior to introduction into the natural gas transmission lines. On occasion the shale gas processing facilities want to burn the stranded high ethane fuel that results from the stripping process. The Wobbe Index of the ethane fuel is 56 MJ/Nm^3. Conventional engine models are capable of using high ethane fuels.

COMBUSTION PARAMETERS AFFECTED BY FUEL COMPOSITION

Wobbe Index is not the only fuel parameter that is used in evaluation of a fuel’s suitability for *SoLoNOx* applications. Any fuel delivered to a conventional or *SoLoNOx* engine must be at a temperature above the dewpoint by a minimum of 28°C at the skid edge to prevent condensation of liquid hydrocarbons and two-phase flow in the package fuel system. The gaseous fuels composition can influence some fundamental combustion parameters that must be assessed to ensure reliable operation and durability. The most critical and unique parameters for the lean-premixed *SoLoNOx* combustion system are combustion stability, autoignition delay time, and flame speed. The dewpoint, autoignition delay time and laminar flame speed for typical types of associated gases compared to pipeline gas are also included in Table 1.

Combustion Stability is characterized by the presence or lack of significant levels of combustor pressure oscillations or combustor rumble. Combustor pressure oscillations occur when the heat release from the flame couple with pressure waves at an acoustic mode of the combustor. Combustor rumble occurs when the combustor or some portion of the combustion volume is operating near the flame extinction point. In either case, if an instability reaches a critical pressure amplitude, damage to the combustor liner or attachments to the turbine section will occur. Engine qualification is required to verify that different fuel compositions do not significantly change the combustion stability characteristics.

Autoignition Delay Time (AIDT) is the time that an air and fuel mixture at a given initial pressure and temperature will require to auto-ignite. In the premix section of the *SoLoNOx* fuel injector, it is critical that ignition and flame stabilization do not occur because the injector integrity would quickly be compromised from the elevated temperatures. Note that for autoignition to occur in the continuous flow found in the premixer, the AIDT must be shorter than the residence time of the fuel air mixture as it flows from the fuel injection point inside the injector to the flame front in the combustor volume.

The AIDT values listed in Table 1 are ideal values that are calculated assuming the fuel and air are homogeneous and perfectly premixed. Autoignition delay is influenced by the mixture’s pressure and temperature, fuel type, air-to-fuel ratio, and localized fuel variation. The AIDT is also affected by the flow field and the turbulence intensity and variation. The fuel-air mixture pressure and temperature and flow field variation within the fuel injector differ significantly by engine model. The auotignition delay time for different reference fuels characterized by different wobbe indices have been determined in high pressure single injector rig tests using fuel injectors for each of Solar’s engine models. Chemkin-Pro is used to computationally predict the AIDT in an ideal system using NUI Galway Reaction Mechanism. The ideal AIDT is used to compare different fuel types and compositions to assess the risk of a flame autoigniting in the fuel injector premixer section.

With pipeline quality gas, the AIDT in *SoLoNOx* fuel injectors is typically less than one tenth of the available bulk stream residence time. While the bulk stream residence time may be much shorter than the AIDT, it is really the residence time in the longest fluid streamline that is at greatest risk of autoigniting. For example, a recirculating eddy from a flow separation along the premixer wall would have a significantly longer residence time than the bulk stream. Quantifying the longest realistic residence time is often difficult, therefore, to minimize the autoignition risk a large ratio of bulk stream residence time to AIDT is used. Another location in the injector subject to autoignition is in dormant gas fuel passages found in dual fuel injectors while operating on liquid fuel. Solar has implemented robust solutions to avoid such risks by purging the gas passages to prevent collection of static combustible mixtures that could autoignite. Figure 2 is a plot showing the relation between autoignition delay time and fuel type. Gaseous fuels with large concentrations of methane generally have longer AIT, while those with more reactive species such as hydrogen sulfide, alkenes, carbon monoxide, and heavier alkanes can have significantly lower delay times.

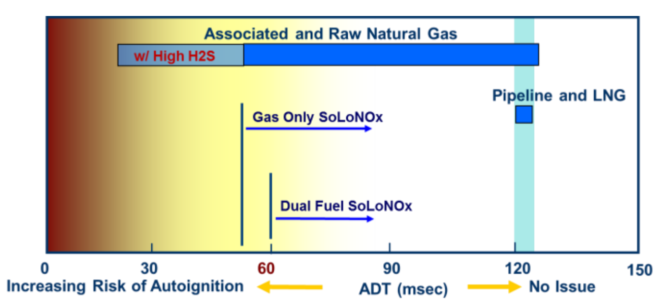

Figure 2. Comparison of Ideal Autoignition Delay Time for Associated and Raw Natural Gases at Gas Turbine Conditions

Flame Speed is the speed that a flame will propagate through an air-fuel mixture at a given temperature and pressure. The flame speed must be significantly less than the mixture velocity in order to prevent the flame from pulling into the injector premixer. Again, this is generally considered by quantifying the bulk stream velocity in the premixer, but any streamline of lower velocity is at risk of providing a conduit for the flame to pull back. Generally, in a well-designed injector premixer, the part of the flow field that is at greatest risk is along the walls in the boundary layer. When a flame propagates upstream in the boundary layer it is often called “flashback”. While it is essential that the flame speed be less than the mixture velocity, it is equally important that the flame speed not be too low either. If the flame speed is too low, the flame will not stabilize at the right location in the combustor primary zone and the flame will blow out.

The flashback propensity and lean blow out characteristics were determined for different reference fuels by Wobbe Index in a high pressure single injector combustion rig for each engine model’s fuel injector. The flashback risk for each fuel is determined by comparing the laminar flame speed calculated at reference conditions against a reference fuel. The comparison is made using laminar flame speed rather than turbulent flame speed for simplicity. Chemkin Pro’s 1-D computational software is used to predict the laminar flame speeds for the freely propagating flame using GRI Reaction Mechanism, enhanced with Lawrence Livermore National Laboratory Reaction Mechanism for the hydrocarbon molecules larger than propane.

The relation of laminar flame speed with fuel type is shown in Figure 3. The laminar flame speed of pipeline quality natural gas is shown to be approximately 125 cm/sec. As long as the fuel-air mixture velocity in the injector premixer is greater than the turbulent flame speed, flashback will not occur. As is evident in the figure, associated gas and raw natural gas fuels have a much broader range of laminar flame speed than pipeline gas owing to greater variability in their composition. Heavier alkanes and unsaturated hydrocarbons lead to higher laminar flame speeds while CO_2 and N_2 slow the laminar flame speed.

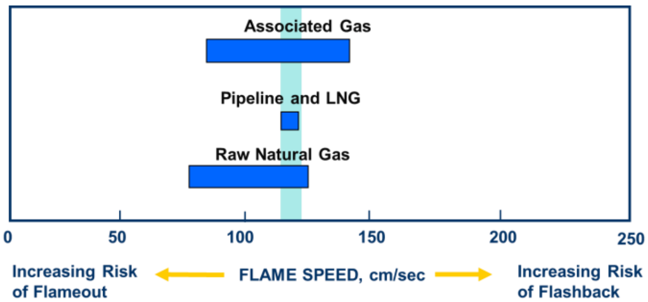

Figure 3. Greater Laminar Flame Speed Variation for Associated Gases Due to Composition

EXPANDING *SOLONOX* FUEL FLEXIBILITY

Solar has expanded and is continuing to expand the gaseous fuel flexibility of *SoLoNOx* gas turbines. In Figure 4, the development path as a function of Wobbe Index capability is depicted showing the different phases completed. *SoLoNOx* standard fuel capability is indicated with blue shading. The green shaded sections labeled Phase 1 and 2 were completed to enable *SoLoNOx* engines to operate on high and medium wobbe associated and raw natural gases. These are the most commonly occurring segments of these gases. The development work targeted all of Solar's engine families that are available with *SoLoNOx* including the Centaur™, Taurus™, Mars™ and Titan™ models. In addition, development is completed on both the gas only and dual fuel configurations. In Phase 1, the high wobbe gases were qualified. As indicated in Table 1 these gas fuels typically contain higher concentrations of ethane, propane, and butane than pipeline quality natural gas fuel. These gases are found in many parts of the world including the North Sea, Gulf of Mexico, Western Africa and much of the Middle East. Associated gases typical of oil fields in the western Pacific, include significant quantities of CO_2 and have a Wobbe Index below current *SoLoNOx* capability. The medium wobbe fuels were developed next in the Phase 2 program. The final phase of development to handle the lowest wobbe associated gases is in progress.

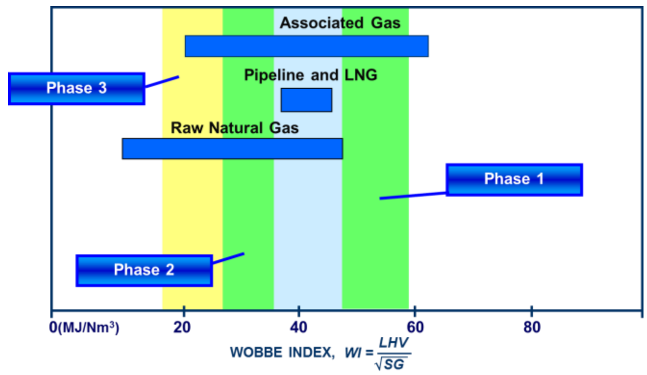

Figure 4. SoLoNOx Development Path to Expand Associated and Raw Natural Gas Capability

Development Tools. In order to expand gaseous fuel flexibility with *SoLoNOx* gas turbines, experimental and analytic tools have been used. Commercially available 1-D analysis tools, such as CHEMKIN-PRO, and 3-D CFD analysis tools, such as STAR CCM+, are used to understand the fuel flow characteristics and the heat transfer in the combustion system. The analytical work helps to efficiently plan experimental work to reduce the design time. Using these state-of-the art tools have enabled Solar to complete a more comprehensive qualification with associated gas to bring this capability to market faster.

A fuel blending system, as shown in Figure 5, has been installed to allow rig and engine testing at the factory with up to four blended fuel streams including: natural gas (pipeline), propane, butane, and CO_2 for lower BTU fuels. The system consists of large storage tanks for two hydrocarbon fuels (typically, propane and butane), and one tank for a diluent, typically CO_2. These fuels are heated and mixed in appropriate proportions to simulate associated or raw natural gases. The mixture proportions are checked with an on-line gas chromatograph. The simulated gas mixture is piped to rig or engine test cells through a heat traced line to prevent condensation and liquid drop-out of the propane or butane. For engine tests, a surge tank is installed as well as a flare system, to accommodate large engine load transients, start-up, or emergency shut-down events during testing, to safely handle and eliminate these fuel mixtures.

Figure 5. Fuel Blending Facility Used for Rig and Engine Testing.

Qualification Process. The qualification test program is completed in multiple steps. Standard test fuels to simulate associated gas are created by blending pipeline gas with propane, butane and CO2. The standard medium and high wobbe fuels are included in Table 2. The standard test fuels were created to simulate the wobbe, flame speed and autoignition ranges seen with the full range of associated and raw natural gases.

Instrumented injector screening is completed in high pressure test rigs to define under what conditions that flashback or blow-out occur for each of the test fuels. This is completed with thermocouples mounted in the premixer section of the fuel injector that are monitored for temperature rise. The combustion test rigs also allow for visual observation of the flame position. Emissions are also measured in the combustion rig. An initial assessment of the injector durability by operating on different associated gas blends are completed by measuring hardware temperature by using thermally sensitive paint.

Following the rig tests engine testing is completed to fully characterize the performance on the different test fuel blends. The engine is used to measure emissions across the operating load range with each fuel along with the combustion stability characteristics. Combustion stability is mapped to identify that appropriate pilot settings are defined across the operating range so that combustor pressure oscillations and rumble are avoided. In addition to steady state operation the engine is operated through real world transient scenarios such as engine start-up and shut-down as well as sudden load changes. Detailed hardware temperature mapping is also completed to validate that component temperatures are maintained at acceptable levels.

		Associated Gases				
	Std NG	800	1000	#1	#2	#3
Wobbe (MJ/Nm3)	43	28	35	48	51	56
Methane (%vol)	93	71	83	74	68	51
Ethane (%vol)	4	3	4	3	3	2
Propane (%vol)	1	0.6	0.7	21	19	30
Butane (%vol)	0.2	0.1	0.2	0.1	9	15
CO2 (%vol)	2	24	11	0.4	0.3	0.2
Dewpoint (C)	-37	-27	-32	13	42	62
Flame Speed (cm/sec)	121	104	115	135	140	145
Autoignition Time (msec)	124	125	124	110	66	60

Table 2. Standard High and Medium Wobbe Test Fuels for Rig and Engine Qualification.

Test Results. Figures 6 and 7 indicate the effects of associated gas wobbe index on emissions and combustor liner wall temperatures, respectively. This data was taken on a Titan™ 130 engine. In Figure 6 it is clear that emissions are increasing as wobbe index is increased. Associated gas fuels with higher concentrations of heavier hydrocarbons have higher adiabatic flame temperatures than natural gas. As such, they have higher NOx emissions as indicated in the Figure 6. In addition to the higher adiabatic flame temperature, a secondary effect due to fuel mixing variation is also most likely contributing to the higher NOx emissions with the higher Wobbe Index fuels. This variation results from using the same fuel injector hardware and then operating at substantially different fuel flow rates needed for each Wobbe Index. The momentum ratio of the fuel mixing with the air is not constant with Wobbe Index. The extent of this effect has not been quantified but can be no more than several ppm. Finally, it should also be noted that while the test results indicate that the highest wobbe gas yields nearly a two-fold increase in NOx the target of less than 25 ppm is met with margin for all test fuels.

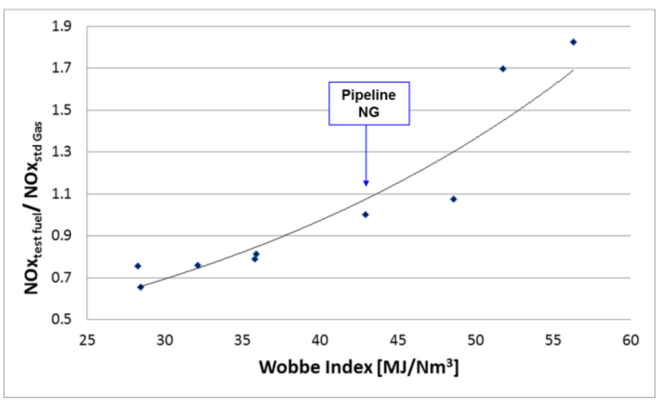

Figure 6. Full Load NOx Performance of a Titan™ Engine Operating at Minimum Pilot with Associated Gas Test Fuels.

The higher flame temperature seen with the higher wobbe fuels is not as evident in Figure 7, which shows the variation in combustor liner wall temperatures for the different test fuels. In addition to the thermocouple measurements in Figure 7, engine hardware metal temperatures were also validated by the use of thermal paint and/or thermal crystals. The results from all these measurements indicate that operation with associated gas is comparable to that with standard pipeline gas. Temperatures are acceptable for the materials used and will allow the standard time between engine overhauls. Associated gas operation performance did not differ appreciably between the gas only and dual fuel configurations.

CONFIGURATION CHANGES

Hardware and software changes that are required when using different associated gases are summarized in Figure 8. The intent has been to minimize the number of changes that are required to provide operators with greatest fuel flexibility with fewest interruptions in operation. With the gas only system in the medium and high wobbe ranges very few changes are required as indicated. With the dual fuel configuration the changes to the fuel injector, package system and controls can be more extensive when using very low AIDT fuels.

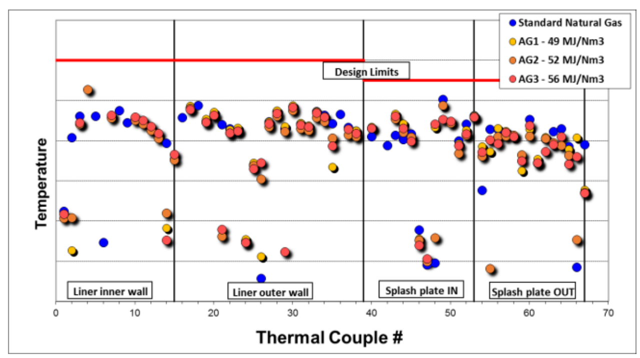

Figure 7. Combustor Liner Wall Temperatures From a Titan™ Engine Running at Full Load with Various Associated Gas Test Fuels.

High temperature insulated and/or heat traced fuel systems are required with high wobbe fuels to prevent condensation of the heavier hydrocarbons. Finally, associated gases with significant hydrogen sulfide require material change for certain fuel system and combustion system components.

EXPERIENCE

As *SoLoNOx* engine models have been qualified, projects with high and medium wobbe associated and raw natural gases have been completed. The earliest shipments have been in operation for multiple years with most of the early shipments completing an overhaul. Operationally, these *SoLoNOx* engines run on associated gases in much the same was as they operate on pipeline natural gas. As with all DLE gas turbines, fuel quality with adequate fuel treatment is a pre-requisite for trouble free operation. A summary of Solar units operating with associated and raw natural gas is included in Table 3.

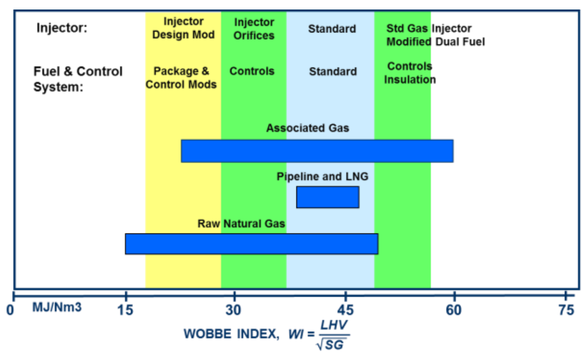

Figure 8. Engine and Package Changes Required with Different Associated Gas Fuels

Engine	Conventional	SoLoNOx
Saturn	>1100	-
Centaur	>1200	>60
Taurus 60	>500	>120
Taurus 70	>150	>40
Mars	>400	>80
Titan 130	>175	>90
Titan 250	2	>5
Total Units	>3500	>400

Table 3. Shipments into Applications Using Associated and Raw Natural Gas Fuels.

SUMMARY

SoLoNOx engine models have been qualified for operation on high and medium wobbe associated gases. The qualification has validated that the gas turbine operation in terms of emissions, durability and performance is acceptable. For most applications only minor changes to the fuel injector, fuel system, and engine controls are required. However, for dual fuel applications with very high flame speed associated gases (typically high wobbe gases) more extensive changes including a dedicated fuel injector and purge system are required. Qualification of lower wobbe fuels is currently in work. Field experience from numerous shipments of *SoLoNOx* engines have indicated that the system is robust and durable when operating on the full range of associated and raw natural gases.

REFERENCES

[1] *"Composition of natural gas". Naturalgas.org.*

[2] ASTM D2597-94, 1994, "Standard Test Method for Analysis of Demethanized Hydrocarbon Liquid Mixture Containing Nitrogen and Carbon Dioxide by Gas Chromatography," pp 121-11.

[3] Cowell, L.H., Etheridge, C., and Smith, K.O., "Ten Years of DLE Industrial Gas Turbine Operating Experiences. ASME, GT-2002-30280. 2002

[4] Glassman, I., 1987, Combustion, Second Edition, Academic Press, Inc.

[5] Janus, M.C. and Richards, G.A., Characterization of Oscillations During Premix Gas Turbine Combustion,"ASME 97-GT-244

[6] Solar, Specification ES 9-98, 2015, "Fuel, Air and Water (or Steam) for Solar Gas Turbine Engines," Solar Turbines Incorporated, San Diego, California.

[7] US Energy Information Administration. 2010. International Energy Statistics. http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=3&pid=48&aid=1&cid=regions&syid=2007&eyid=2011&unit=BCF (accessed 11 April 2016).

[8] CHEMKIN-PRO 15131, Reaction Design: San Diego, 2013

[9] D. Healy, D.M. Kalitan, C.J. Aul, E.L. Petersen, G. Bourque, H. J. Curran, “Oxidation of C1-C5 Alkane Quinternary Natural Gas Mixtures at High Pressures”, Energy and Fuels 24(3) (2010) 1521-1528.\

[10] GRI-Mech3.0, http://www.me.berkeley.edu/gri mech.

[11] Curran, H. J., P. Gaffuri, W. J. Pitz, and C. K. Westbrook, "A Comprehensive Modeling Study of n-Heptane Oxidation" Combustion and Flame 114:149-177 (1998).