19TH SYMPOSIUM OF THE INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE
BANFF, ALBERTA, CANADA
OCTOBER 17-19, 2011

11-IAGT-101

SATISFYING THE LNG INDUSTRY'S REQUIREMENTS FOR AGILE OPERATION ON HIGH C2+ AND INERT CONTENT GAS FUELS IN ROLLS-ROYCE AERODERIVATIVE INDUSTRIAL GAS TURBINES

Brian J Nolan

Rolls-Royce Canada Ltd, 9545 Cote de Liesse, Dorval, QC, Canada
(brian.nolan@rolls-royce.com)

Abstract

Beginning in the mid 1960's, the oil and gas industry has seen a steady growth in the use of liquefied natural gas (LNG) as a means to transport gas from its extraction point to world markets. The primary driver for liquefying natural gas is that the significant reduction in volume, approximately 1/600th the volume of natural gas in the gaseous state, allows it to be more efficiently transported over long distances by sea or land, where high capital investment infrastructure may not exist. The growth in the use of LNG as a means to transport energy has been driven by a number of factors, including exploitation of gas reserves further off-shore or in regions of the world distant from natural gas markets.

The nature of LNG transportation to its end-user market tends to be intermittent (e.g. by ship) rather than continuous (e.g. by pipeline). This intermittent nature presents increased challenges to LNG plant operators in regards to logistics management. The availability and reliability of plant equipment is a key requirement to ensure that LNG is ready for loading and shipping to avoid costly delays and penalties.

Due to their high power density, gas turbines are frequently used as the primary power source for refrigerant-gas compressors used in the LNG liquefaction plant and for the generation of site electrical power. The ever increasing demand for high availability and reliability has seen a growing shift towards aero derivative gas generators as the power source of choice.

Rolls-Royce Energy has experienced an increasing demand for aero derivative gas turbines in LNG applications. Process design of the LNG plant frequently results in an envelope of high C2+ and high inert gas for use in the gas turbine so that the LNG exports can be maximised. Due to this increasing demand, Rolls-Royce Energy responded by launching analysis and testing to validate whole engine functionality for the envelope of gas mixtures used by our customers in these applications. The purpose of this paper is to summarise the methodologies used and the progress made by Rolls-Royce in both our Dry Low Emissions (DLE) and conventional combustion aero derivative gas turbines.

1 Introduction

The oil and gas industry has seen a steady growth in the use of liquefied natural gas (LNG) as a means to transport gas from its extraction point to world markets. Historically, oil and gas orders tended to favour non-DLE (conventional) over DLE variants. In this decade, there has been a notable trend toward DLE. In the past, low emissions requirements were applicable to onshore applications only and were not applicable to offshore applications. World emphasis on reduction in pollutants is driving the onshore requirements to be applied to offshore applications.

LNG applications provide particular challenges to a prime mover. These logistic-critical applications require high availability and reliability of power provision, with operation on a wide variety of fuels. Agile operation with starting, rapid load changes and on-line transfer between significantly varying fuel-types are frequently key requirements. The aim of this paper is to explore the key operational and functional challenges of an aero-derivative gas generator in an LNG application. The paper will then go on to present some of methodologies employed by Rolls-Royce to increase the operational and functional envelope appropriate for LNG application fuels. Recognising the market trend towards DLE, in 2004 Rolls-Royce launched a combustion initiative on the RB211 DLE to understand the effect of high concentrations of Inerts and C2+ with the goal to verify operation of a wide range of fuel compositions. Rolls-Royce has developed experience in applications requiring high C2+ or inert on a number of its products, however, this paper intends to use the examples of the industrial RB211 conventional combustor and the initiative to extend the RB211 DLE capability.

2 Typical LNG application requirements

The primary purpose of a generic LNG plant is to liquefy natural gas by lowering the temperature to approximately -160 degrees Celsius. This causes the methane (and some ethane) present in the gas mixture to condense to a liquid making transportation at atmospheric pressures feasible. To achieve this, natural gas from the well must be processed and conditioned to dehydrate and remove acidic gases and heavy hydrocarbons (C2+). Raw gas from the well often contains high CO_2 or N_2 levels which also become a by-product of the methane liquefaction process. The LNG produced in the process is typically loaded to tankers for sea shipping. The LNG loading from plant to tanker is, by its nature, intermittent. In a process referred to as autorefrigeration, the LNG is kept a boiling point during transportation. This evaporative cooling of the LNG serves the keep the residual liquid at the required temperature.

Figure 1 below provides a typical simplified LNG plant schematic.

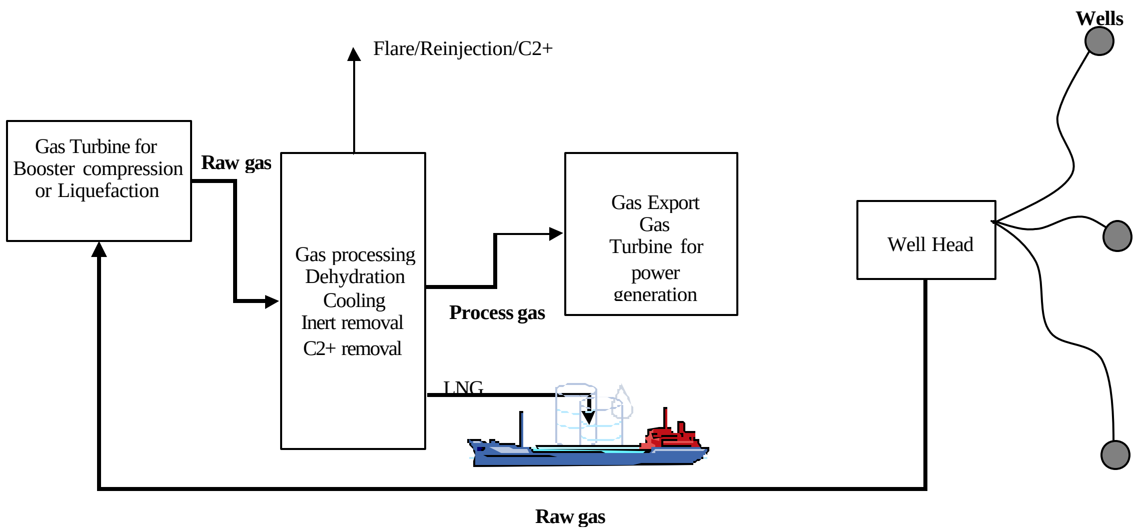

Figure 1: Simplified LNG plant layout

The nature of the gas processing in an LNG is such that, derived from the raw gas taken from the well, gas of a wide range of compositions in regards to its inert (CO_2 or N_2), C1 or C2+ content becomes available at various stages of process or under transient operations, such as start-up, shutdown, fault or LNG off-load. Gas Turbines can be used for power in a variety of applications in such an example plant schematic, such as site electrical power generation, compressor boosting of raw gas, refrigerant compression for gas cooling, process gas compression or waste gas compression for reinjection into the well to maintain pressure and output. Raw gas composition itself tends to change over time as the well degrades, particularly where reinjection is used. Colleague

To provide optimum process flexibility, the gas turbine will be required to run on as wide a range of these gas specifications as possible and accommodate raw gas evolution as the well degrades. Table 1 below provides a representative example of gas mixtures the gas turbine could be expected to operate on.

Table 1: Example spectrum of fuel types in LNG

Description		Normal Operation	Normal Start	Fault Start 1	Fault Start 2	Fault Start 3	Compressor Trip	Booster Trip
Composition:								
CO2	mol%	0.00	3.00	0.00	0.00	0.00	0.00	0.00
Nitrogen	mol%	9.16	0.91	0.94	1.05	20.30	1.02	9.05
Methane	mol%	82.38	76.55	78.91	88.45	79.69	85.84	84.77
Ethane	mol%	8.32	9.83	10.13	10.26	0.01	12.91	6.04
Propane	mol%	0.13	6.65	6.86	0.23	0.00	0.22	0.13
i-Butane	mol%	0.00	0.89	0.92	0.00	0.00	0.00	0.00
n-Butane	mol%	0.00	1.45	1.49	0.00	0.00	0.00	0.00
i-Pentane	mol%	0.00	0.23	0.24	0.00	0.00	0.00	0.00
n-Pentane	mol%	0.00	0.39	0.40	0.00	0.00	0.00	0.00
n-Hexane	mol%	0.00	0.05	0.05	0.00	0.00	0.00	0.00
n-Heptane	mol%	0.00	0.04	0.04	0.00	0.00	0.00	0.00
n-Octane	mol%	0.00	0.01	0.01	0.00	0.00	0.00	0.00
H2O	mol%	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H2S	mol%	0.00	Max 5 ppmv	Max 2ppmv	Max 2 ppmv	0.00	0.00	0.00
Total	mol%	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	C1	82.38	76.55	78.91	88.45	79.69	85.84	84.77
	C2+	8.45	19.54	20.14	10.50	0.01	13.14	6.18
	inerts	9.16	3.91	0.94	1.05	20.30	1.02	9.05

3 Non-DLE Gas generator operational considerations

As shown in section 2, typical LNG applications can expose the gas generator to a wide range of C2+ and inter gas fuels under steady operation and transient condition. This section will summarise the key implications of operating on those gas fuels for the gas generator, using the RB211 non-DLE as an illustrative example.

3.1 Combustor overview

The RB211 conventional aero-derivative combustion system, referred to as the "Phase II Dual Fuel", is an 18-burner annular design. Figure 2 below provides a simplified cross section view of the combustor.

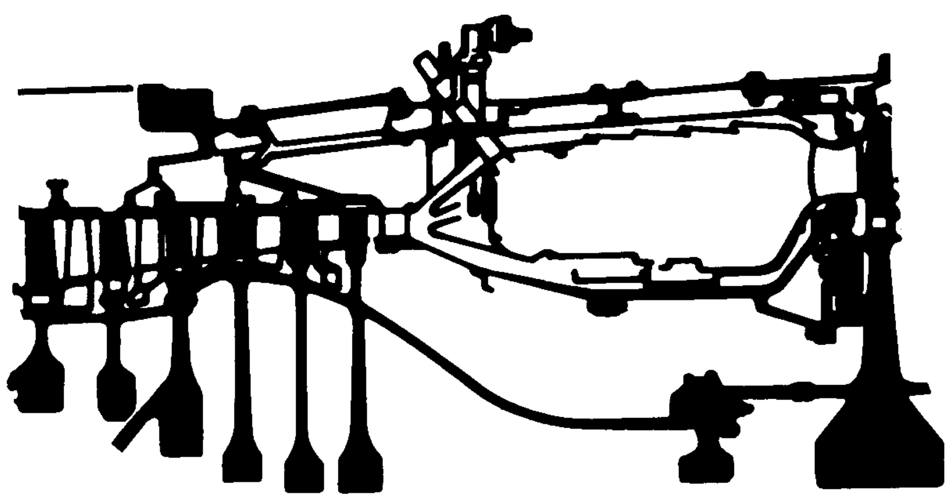

Figure 2: RB211 conventional non-DLE combustor

Gas fuel flows through a manifold tube that distributes it to the 18 individual burners via flexible pipes. The gas is injected into an annular combustion liner where it is mixed with compressed air from the high pressure compressor to form a diffusion flame. The hot gas mixture passes through the high pressure nozzle guide vane and is expanded in the high pressure turbine where work is extracted from the gas.

The Wobbe Index [Ref1] is a calculated gas property incorporating the heating value of a fuel and its specific gravity. The Wobbe index or number is typically used to compare the combustion energy output of different gas fuels at fixed pressures and settings. For a given energy output, increase Wobbe index generally implies lower gas pressure, lower injector speeds and lower fuel mass-flow. Decrease in Wobbe index implies the opposite. Increase in inert has the effect of lowering the Wobbe index. Increase in C2+ has the effect of increasing the Wobbe index. In summary, LNG applications exposes the gas generator to a range of Wobbe index fuel higher and lower than standard natural gas applications.

The following subsections summarise the key considerations for assessment by the gas generator OEM as the inert and/or C2+ content changes .

3.2 Fuel ignition and stable flame

Reaching stable idle conditions depends on many factors, including but not limited to fuel characteristics, air to fuel ratio, combustor flow patterns, fuel flows, fuelling ramp rates & cranking speeds. For a given engine type, all except fuel characteristics will remain relatively constant. LNG application fuel compositions can affect air-to-fuel upper and lower flammability limits and injection speed and momentum changes can affect fuel placement relative to fuel spark-igniters during the ignition and start sequence.

3.3 Burner injection velocity

The potential penalty of increasing injection velocity is combustor instability and/or high metal temperatures caused by high momentum fuel escaping the normal re-circulation patterns and burning close to the flame tube walls. Injection velocity change can also potentially alter the temperature profile experienced by turbine vane and rotors.

3.4 Combustion Rumble

Combustion rumble is a potential phenomenon normally associated with high Wobbe index fuels. The theoretical limit is considered to be that the fuel injector velocity head must be greater than the air velocity head across the combustor. Failure to achieve this criterion can potentially result in combustor rumble (audible instability) caused by interaction of combustion of air and fuel in the engine and the fuel control.

3.5 Delivery system pressure limits

Low Wobbe index fuels increase working pressures and flow velocities of the fuel delivery systems. These increases need to be assessed as within the design margin of the fuel delivery system.

3.6 Liquid condensates

As the C2+ content increases, the dew point (the temperature at which certain constituents of the fuel being to coalesce to a liquid) of the gas fuel increases. Liquid condensates in a gas fuel burn inconsistently and cause an abnormal force input into rotating turbine equipment, potentially causing high-cycle fatigue damage. This is mitigated by increasing the gas fuel temperature, which has the knock-on effect of increasing the working pressures in the fuel delivery systems (see section 3.4)

3.7 Compressor working lines

Axial compressor operating points are typically mapped on a plot with the horizontal axis representing compressor non-dimensional (normalised for inlet pressure and temperature) mass-flow and the vertical axis representing pressure ratio (total outlet pressure over total inlet pressure) across the compressor. For a given non-dimensional mass-flow, increasing the pressure ratio will eventually lead to aerodynamic stall on the compressor aerofoils and a breakdown or reversal in air flow though the compressor. Joining a line of pressure ratios where this occurs for a given non-dimensional mass-flow is called the surge or stall line. The pressure ratios where the engine operates for a given non-dimensional mass-flow is referred to as the working line. When additional (e.g. increased gas fuel inert content) flow is added to the combustor between the compressor and turbine, the compressor working line moves closer to the surge line i.e. the surge margin is reduced. This effect is caused by the increase in volumetric flow out of the combustor and also due to the change in combusted gas product properties altering the effective turbine capacity.

4 DLE Gas generator operational considerations

4.1 Combustor Overview

The generic considerations presented in section 3 for a non-DLE combustion are also valid for a DLE gas generator. The DLE variant, however, introduces some additional criterion when LNG application fuel are considered. The RB211 DLE combustion system consists of nine individual combustion cans or “pots”. Figure 3 below provides a simplified cross-section view of one of the RB211 DLE combustion cans. The RB211 DLE operates in two modes. The first mode, in effect at start-up and low powers is diffusion mode operation where gas fuel is introduced though a central fuel injector in each combustion can. When a particular combustion temperature threshold is reached, the engine fuel control system initiates a transfer from diffusion mode to DLE pre-mix mode. The gas through the central fuel injector is turned off whilst seamlessly introducing gas, premixed with air from the axial compressors, into two injectors in each can. These are called the primary and secondary injectors. The premixed air and gas fuel mixture, injected in this staged configuration enables accurate control of optimal combustion temperatures to minimize combustion product emissions such as oxides of nitrogen and carbon monoxide.

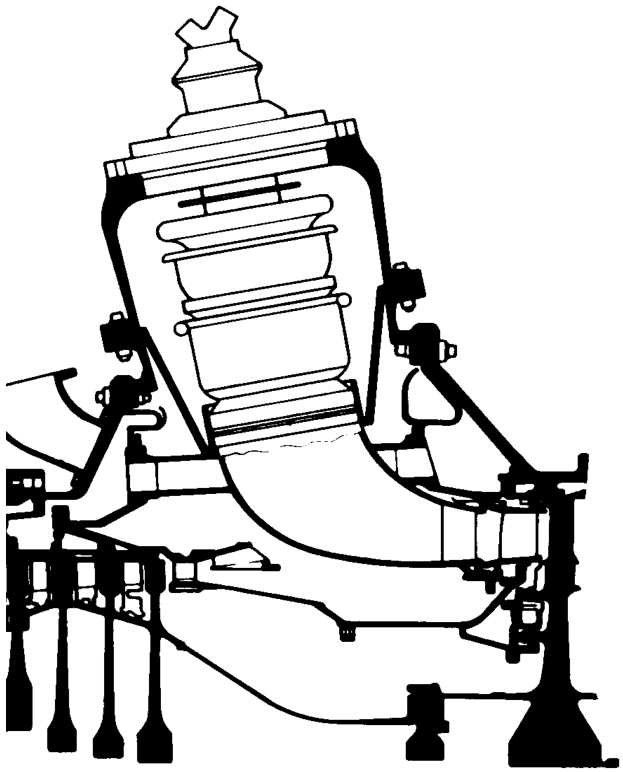

Figure 2: RB211 DLE combustor

Transfer between operational modes, premixing the fuel and undergoing combustion under leaner (lower fuel:air ratios) conditions add additional considerations for the DLE machine operating on LNG application type fuels, summarised below

4.2 Autoignition/flashback

The autoignition temperature for an air-fuel mixture is the temperature required to cause combustion without the need to provide a source of ignition. This is governed by the air-fuel mixture constituents and the air temperature and pressure. Higher than ambient conditions, such as those of the delivery air from the gas turbine compressor, will lower the autoignition temperature. Should this autoignition temperature drop low enough due to the introduction of C2+ content, combustion could occur in the DLE premixer prior to entering the combustion chamber, causing thermal distress.

4.3 Emissions control

Inert content in the fuel can have the effect of quenching the peak flame temperature. Certain C2+ constituents can have the opposite effect. The DLE temperature control system needs to be able to accommodate these changes, controlling the temperature in the primary and secondary combustion zones such that emissions output remains constant.

4.5 Combustion noise

Combustion noise is an interaction between acoustic waves, aerodynamics, and heat release and can become problematic when the point of heat release is close to the point of maximum pressure. DLE systems use various methods to overcome this: by their injector and combustor architecture but also by automated control changes during operation. On the RB211 DLE, one of the control methodologies used is to introduce variable fore/aft biasing in each half of the secondary injector. This can be autonomously enacted to decouple the point of heat release and the acoustic wave by subtly changing fuel placement. Introduction of inert and C2+ can change flame speeds, positions and concentration of heat release, changing the noise frequency bands and amplitudes of the DLE machine.

5 Testing methodology

The RB211 non-DLE conventional combustion variant has had its fuel inert and C2+ constituent agility developed and validated over a number of years and gained considerable running experience. Recognising the market trend towards DLE, in 2004 Rolls-Royce launched a combustion initiative on the RB211 DLE to understand the effect of high concentrations of inerts and C2+ with the goal to verify operation of a wide range of fuel compositions. Initially launched with ethane, later phases of the initiative introduced higher order fuels, such as propane and butane in combination with N2 as this inert in a series of experimental rig testing

5.1 Test conditions

Testing was carried out in a single-sector DLE rig. A heavily instrumented production common DLE can and fuel injection system was used. The objective was to explore the envelope with the existing unmodified hardware standard. The rig environment provided the ability to explore a simulated range of ambient temperate and power conditions. An engine flow function method is used to scale the required rig air-flow to accommodate pressure differences between the rig and the engine. Figure 3 below shows a cross-section of the single-sector rig. Figure 4 shows a photo of the rig.

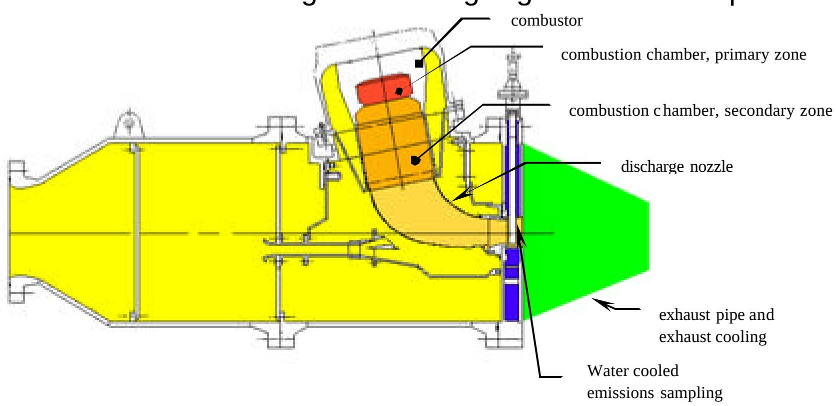

Figure 3: RB211 DLE Rig Test

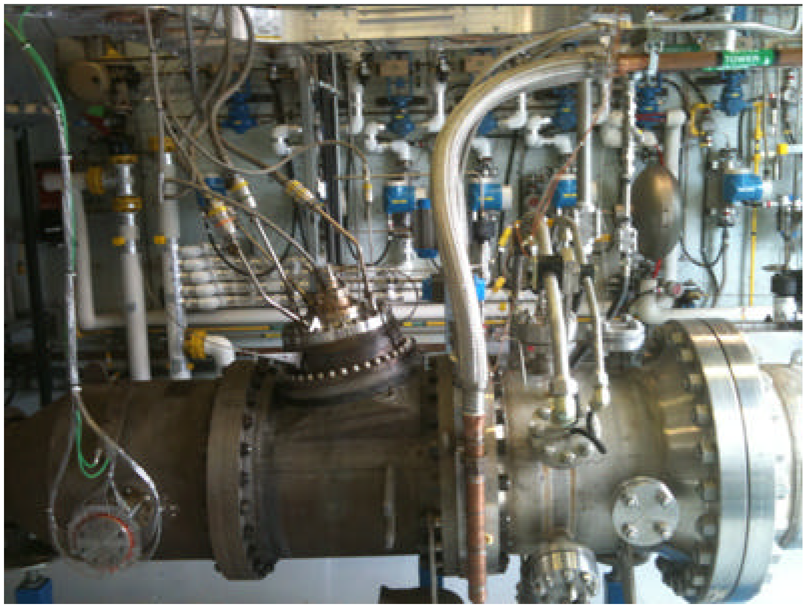

Figure 4: RB211 DLE Rig Test

The rig testing explored the DLE combustor characteristics with mapping carried out for emissions (section 4.3), noise (4.5), ignition and lean blow out (3.2), autoignition (4.2) and metal temperatures (3.3). Other aspects/considerations presented earlier in this paper were validated analytically, were viable for read-across from the non-DLE RB211 or by previously conducted testing or operation experience [Ref2]. The approach used was to construct a test envelope of fuel conditions, starting with typical natural gas constituents and increasing C2+ content by up to 30% and/or inert content by up to 30%. The test envelope created by this approach is depicted in figure 3. The area covered by the rhomboid shape was explored in iterative steps. The content of Methane (X axis) and C2+ are added to make a % less than or equal to 100%. The remaining % required to equal 100% is Nitrogen. For example, from the graph, the top left point of the rhomboid envelope would have tested a gas composition of 35% Methane, 32% C2+ with the residual 33% being N2.

The testing simulated starting and running conditions across the operational envelope. Ethane, propane and butane were used in different tests as the C2+ element.

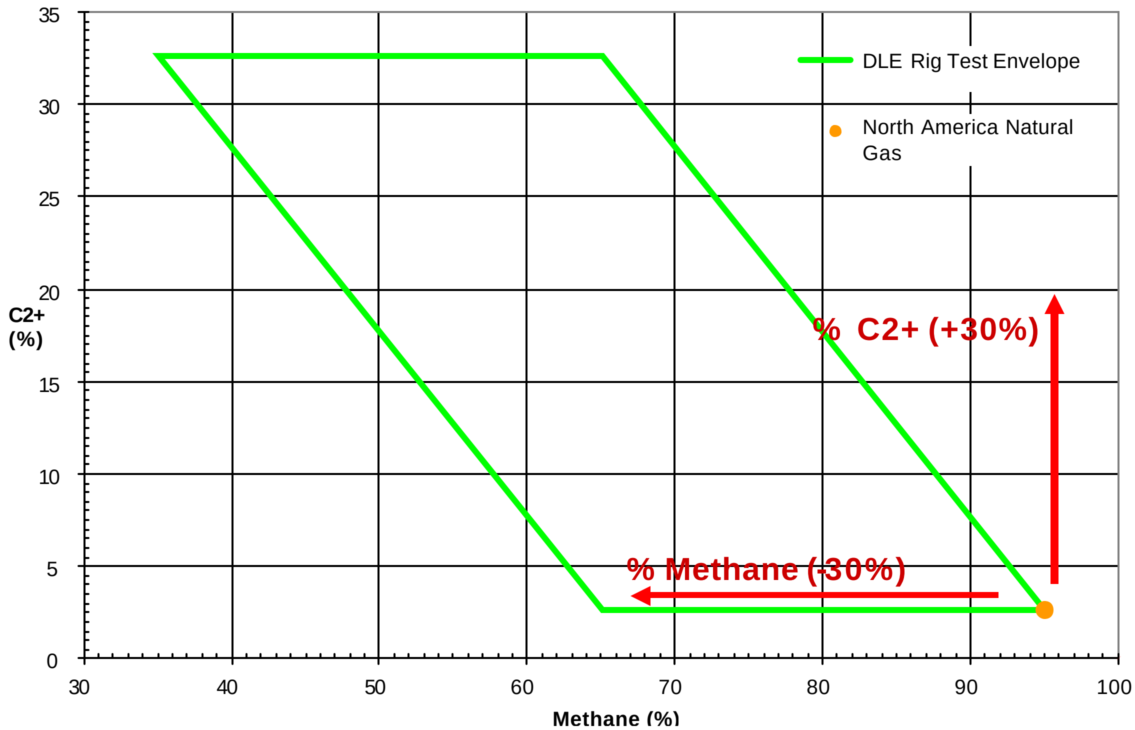

Figure 4: RB211 DLE Rig Test Envelope

5.2 Test outcome

As expected, the test results show a number of interactions between the inert and the C2+ fractions. Indeed the species of C2+ employed played a large role in the setting boundaries of acceptability of various fuel. Drawing a definitive hard line of universal “unacceptability” of a given mixture from this rig testing is not practical. As mentioned earlier in this paper, there are several variables or operability requirements that could occur in an LNG, or indeed any, application (for example, certain gases only being used during starting, gases being delivered with high heavy end (C6+), full load not being required on certain gas mixtures etc). The RB211 DLE, full load and part load, controls emissions, for a given fuel, with a constant primary zone combustion temperature. Although not a liner re lationship, increases in C2+ will tend to increase NOx and decrease CO but also has the effect of lowering the weak extinction temperature. With a lower weak extinction temperature, the primary zone setpoint can we lowered to compensate the NOx increase. Increased inert content has the opposite effect (i.e. lowers NOx for a given primary zone temperature). Case-by-case analysis of fuel is usually required in the context of the full fuel fraction specification and the detailed operational requirements on those fuels. To that end, figure 5 is a summary of categorising zones derived from the rig testing and extrapolation. These zones apply to the standard RB211 DLE combustor without any hardware modification for the specific application.

5.2.1 Zone A – Universally acceptable

Zone A spans the majority of operational service experience of the RB211 DLE. Rig testing and all analytical extrapolations to all reasonable application demands demonstrated no concerns or limitations.

5.2.2 Zone B – Highly likely acceptable for all operational & power requirements

Zone B showed acceptable characteristics for all rig-tested parameters. RB211 DLE has some operational service experience in this zone. Analytical extrapolation to some unusual application requirements may limit some manoeuvres under some conditions. For example, approaching the left side of Zone B (black circle "1" in figure 5), could impose fuel delivery manifold pressure limitations where the inert content was pronominally CO_2 (instead of N_2), gas was supplied at elevated temperatures and the unit was the higher power rated GT standard of RB211. The top edge of the B zone (black circle "2" in figure 5) was the region where the noise signature began to change when high concentrations of butane were present in the fuel mixture, necessitating changes in the primary zone temperature control settings.

5.2.3 Zone C – Case-by-Case fuel and application assessment required.

Zone C showed acceptable characteristics on some C2+ species and would be acceptable for many applications and operational requirements but assessment would be required. The RB211 DLE has limited service experience in this zone. At the top extreme of zone C (black circle "3" in figure 5), concentrations of the lighter species of C2+ (propane and ethane) started to exhibit similar emissions characteristics to butane at the top of zone B. The region between the left side of Zone C (black circle "4" in figure 5) and left side of zone B is an area of higher fuel delivery manifold pressures. In addition, fuel ignition repeatability during start-up begins to decline when C2+ elements are limited.

5.2.4 Zone D1 & D2 – Likely to only be acceptable for limited operational requirements

Zone D showed acceptable characteristics for only limited manoeuvres or powers and hardware modification (fuel delivery manifold sizing etc) would be required to achieve acceptability for a broader range of operations. In Zone D1, on any C2+ fuel, the operational window between lean blow out and noise control becomes impractical without allowing emissions levels to begin to elevate. In zone D2, fuel manifold conditions begin to limit achievable power. Fuel ignition repeatability during start-up is poor in zone D2 when C2+ elements are limited.

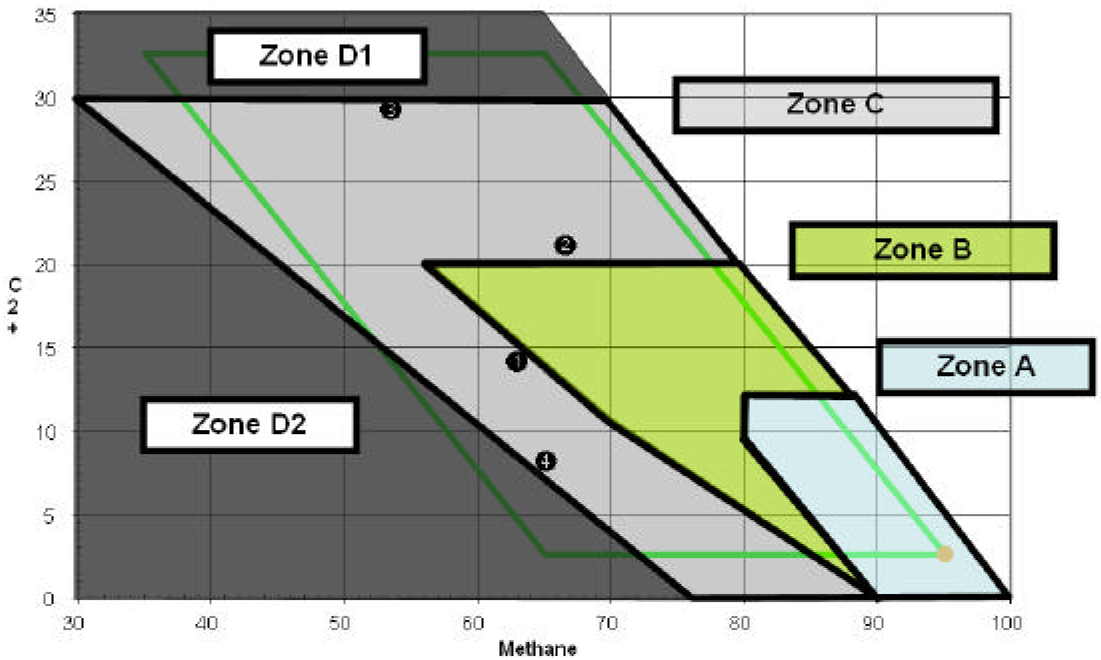

Figure 5: RB211 DLE Fuel Acceptability Zones

6 Summary

The key considerations for a gas turbine manufacturer when considering LNG application fuels have been presented. Rig testing, analytical assessment and service experience read-across has shown that the RB211 DLE machine has the ability to satisfy the operational requirements of a significantly wider inert and C2+ envelope than originally standarised, without hardware change. Due to permutations of inert, C2+, site conditions and required operational maneuvers, the significant number of acceptability criteria a gas turbine manufacturer must consider make it difficult to draw lines of absolute unacceptability and case-by-case analysis is often required.

7 Acknowledgments

The testing and analytical work to understand RB211 DLE operational capability on fuels for the LNG involved the dedicated effort of numerous individuals including, but not limited to:

Julie Beaulac, Rolls-Royce Energy Development Specialist
Gilles Bourque, Rolls-Royce Energy Combustion Engineering Technical Lead
Jerry Blackburn, Rolls-Royce Energy Steady State Performance Specialist
Marc Furi, Rolls-Royce Energy Combustion Specialist
Kevin Goom, Rolls-Royce Energy Applications Specialist
Michel Houde, Rolls-Royce Energy Combustion & Systems Specialist
Louis-Marie Kamoso, Rolls-Royce Energy Combustion Specialist
Brian Price, Rolls-Royce Energy Transient Performance Specialist

8 References

[1] Physical properties of natural gases, N.V. Nederlandsee Gasunie, 1980, p.16.

[2] Development and in-service experience with medium and low BTU gases: ASME 84-GT-20: Development of the RB211-24C industrial gas generator to operate on medium BTU gas., J.D. Willis, 1982