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Effect of GTL-like Jet Fuel Composition on GT Engine Altitude Ignition Performance – Part I: Combustor operability

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ABSTRACT

The current fuel used in aviation turbines is kerosene, and is tightly controlled to a well defined specification. The past 50 years of simultaneous development between the aviation turbine and kerosene jet fuel has led to the fuel specification. The design of the combustion system has also been developed with this fuel chemistry and specification.

In the past 5 years, there has been a ground swell of interest in alternative fuels for aviation, where the fuels can be made from a variety of feedstocks and processes. The chemistry and composition of species within future alternative fuels will change from the current kerosene jet fuel specifications; therefore research has been carried out looking at the effects of some of the fundamental component species that will be found in potential future fuels.

The gas turbine combustion ignition and stability characteristics were studied while fuelled by a series of gas-to-liquid (GTL) Synthetic Paraffinic Kerosene (SPK)-type fuels by measurement of the successful ignition and flame stability regimes at realistic altitude temperatures and pressures. The combustor under test was a multi-sector representation of an advanced gas turbine combustor and fuel injector.

Tests were conducted on the Rolls-Royce plc TRL3 (Technology Readiness Level) sub-atmospheric altitude ignition facility in Derby, UK. The facility was operated at simulated altitude conditions of 6 and 8 psi combustor inlet pressure with corresponding air and fuel temperatures to represent combustor conditions following flame-out during high altitude cruise.

The GTL SPK-type fuels were selected to generate a pseudo-Design of Experiments (DoE) matrix in which the iso- to normal- paraffin ratio, cyclic paraffin content, and carbon number range were varied to isolate the effects of each. Tests were conducted at combinations of air mass flow rate and fuel-air ratio necessary to map the regimes of successful ignition and flame stability.

All fuels indicated little or no deterioration to the weak boundary of the ignition regime, nor the weak extinction limits, within the scatter of the experimental method. Evidence was found that a commercial GTL SPK, as well as one of the DoE blends, may have greater ignition performance at simulated altitude conditions. Further testing at higher TRL levels is recommended to confirm this finding.

The test programme was supported by DLR, German Aerospace Centre, through high-speed diagnostic imaging of the ignition process, including OH* and CH* chemi-luminescence measurements, which is the subject of a separate complementary paper.

1. NOMENCLATURE

CAS	Calibrated Air Speed
CSPK	Commercial Synthetic Paraffinic Kerosene
cyclo	(paraffin)
DoE	Design of Experiments
FAR	Fuel-Air ratio (by mass)
FT	Fischer-Tropsch
GR&R	Gauge Repeatability and Reproducibility
GTL	Gas-to-Liquid

I/n	Iso-to-normal (paraffin ratio)
iso	branched (paraffin)
ISA	International Standard Atmosphere
normal	linear, unbranched (paraffin)
SARS	Sub-Atmospheric Relight Sector
SPK	Synthetic Paraffinic Kerosene
TRL	Technology Readiness Level
W_{31norm}	Normalised combustor air mass flow rate (-)
ft	feet
K	(degrees) Kelvin
kts	knots (nautical miles per hour)
lb s^{-1}	pounds per second
psia	pounds per square inch absolute
Ψ	Equivalence ratio ($FAR/FAR_{stoichiometric}$)

2. INTRODUCTION

2.1 Gas turbine ignition and engine/combustor operability

The aero gas turbine which provides propulsion for the majority of large aircraft in commercial use is required to operate at the extremes of the troposphere and into the stratosphere. It must function in the coldest and hottest day temperatures, as well as the temperate 288.15K of the International Standard Atmosphere at sea-level.

Amongst the key certification requirements for such an engine is the demonstrable ability to relight and return to a stabilised cruise thrust power level following a flame-out and engine run-down at altitude [1]. Previous research into this area on SASOL SPK has been reported in [2].

After these flame-outs at altitude, the pressure and temperature of the inlet air to the combustor is reduced to a small fraction of that in normal operation during the cruise. Depending on the condition and available thrust of the other engine(s) on the aircraft, the aircraft may be maintaining altitude or descending.

The inlet pressure and temperature to the combustor during this flight condition are a function of:

a) Altitude
b) Air speed
c) Engine conditions pre flame-out (especially metal temperature)
d) Turbine aerodynamics
e) Compressor aerodynamics
f) Time since flame-out

2.2 Kerosene fuel specification

Jet fuel is a mixture of different hydrocarbons with a typical carbon distribution varying from 8 to 16 carbons. The hydrocarbons in the jet fuel are mainly a mixture of iso-paraffins, normal-paraffins (n-paraffins), naphthenes (also known as cyclic paraffins) and aromatic-type hydrocarbons. GTL kerosene is a mixture of iso-paraffins, n-paraffins and naphthenes, with insignificant (<0.1% volume) amounts of other components like aromatics. The iso/normal paraffins ratio, as well as total naphthenes/total paraffins ratio, is also different for conventional jet fuel and GTL kerosene.

The primary function of jet fuel is to power aircraft engines. Jet fuel also functions as a hydraulic operating fluid for the engine; it is used to absorb and recycle excess heat from the engine oil system, and has the function of a lubricant for the fuel system. The key properties that serve the primary function of the fuel are combustion quality and the fuel energy content. Other properties such as lubricity, fluidity, and thermal stability are also important for the fuel performance.

2.3 Production of Gas-to-Liquid fuels

Synthetic fuels are a slate of fuel products synthesised from carbonaceous feedstock over Fischer-Tropsch (FT) catalytic process. Synthetic fuels have a paraffinic nature and contain virtually no sulphur or heavy metal traces. These characteristics gave synthetic fuels a unique position in speciality fuel market. Typically GTL fuels are synthesised from natural gas in three main steps: natural gas preparation/conditioning, FT synthesis and product upgrading. The first step is to condition natural gas by splitting condensate and heavier hydrocarbons from methane, followed by hydrogen sulphide (H_2S) and carbon dioxide (CO_2) removal. The last conditioning stage is the gas dehydration (drying) stage. The conditioned gas (mainly methane) will then be converted to produce syn-gas, a mixture of carbon monoxide (CO) and hydrogen (H_2) at a certain ratio. Fischer-Tropsch synthesis rearranges CO and H_2 molecules in long chains of hydrocarbon (paraffins) over a cobalt- or iron-based catalyst.

The product of FT synthesis has to go through a product upgrading (hydrotreating) stage. In the hydrotreating stage paraffins will be isomerised and cracked into shorter chains to meet the finished product quality specifications. This stage will also re-convert and remove the unwanted oxygenates, olefins and heavy molecules. The typical GTL product slate contains synthetic naphtha, synthetic diesel, and heavier products such as lubricants.

Synthetic paraffinic kerosene (SPK) is a cut between synthetic naphtha and synthetic diesel.

3. FUEL SELECTION AND BLENDING

Five blends have been chosen to assess the relationship between altitude ignition performance and compositional structure. Only three compositional variables were selected to design the five blends: carbon number distribution (narrow/wide cut), iso/normal-paraffins ratio and the total cyclic paraffin content, as shown in Figure 1 and Figure 2. Each fuel blend is differentiated from the others with a single or combination of variables, to test the impact of different compositional characteristics on ignition performance. The cube shown in Figure 3 summarizes the compositional characteristic of each blend.

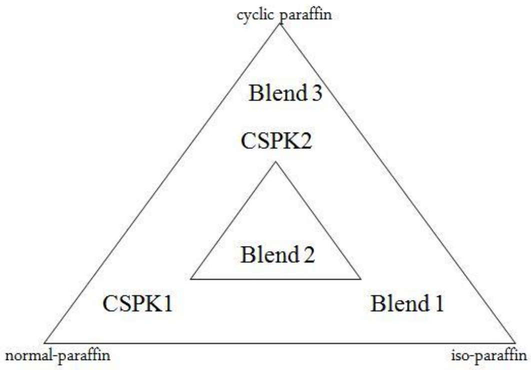

Figure 1 : The fuel triangle, showing fuel blend compositional variables

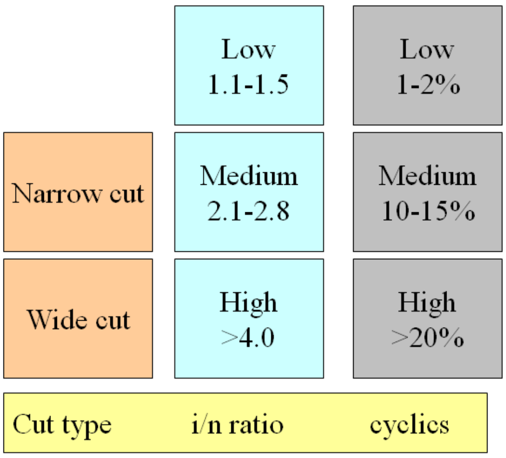

Figure 2 : Fuel blend compositional variables

The cube dimensions were based upon production properties from current and future commercial GTL plants. For future GTL plants, indicative properties from pilot plants were considered. The properties of a reference Commercial Synthetic Paraffinic Kerosene plant (CSPK1) were set as a reference for all other blends.

CSPK1 is a narrow cut (C7-C13) GTL Jet Fuel with iso/normal paraffins ratio of 1.3. On the other hand, the future plant (CSPK2) will have a more isoparaffinic nature with a broader carbon range (C7-C16). The typical cyclic content of Synthetic Paraffinic kerosenes (SPK) from GTL is less than 5% wt but the ASTM D7566 specification for Fischer-Tropsch SPK will permit the total cyclic content to be as high as 15% wt.

All fuel samples contain GTL kerosene product, from CSPK1 which meets D7566 SPK criteria and has already been demonstrated in commercial flights [3]. The volumes of fuel required for the large scale tests in the combustion programme were such that it was not an option to blend a range of pure, single component chemicals to accurately replicate every feature of future GTL-type fuels. Instead, quantities of commercially available paraffinic solvents (ShellSol solvents) were added to CSPK1 to simulate fuels which covered the three chosen compositional variables listed above.

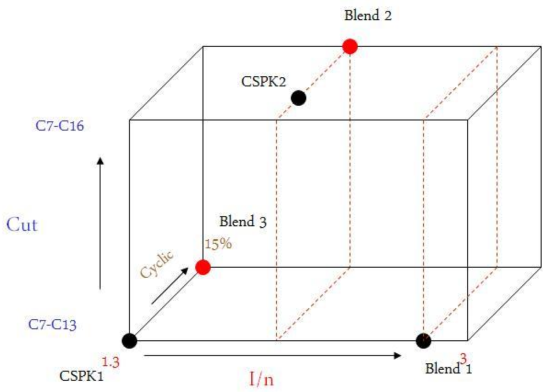

Figure 3 : 3-D fuel blend composition cube

The CSPK2 blend is a blend of CSPK1 base GTL and commercial solvents to mimic the key compositional features of the CSPK2 pilot plant kerosene. It is a wide-cut sample with an iso/normal ratio of approximately 2.2 and a relatively low cyclic content of approximately 5%. Blend 1 is narrow-cut jet fuel with boosted iso-paraffins to normal-paraffins ratio of 2.8. Blend 2 is wide-cut jet fuel with iso-paraffins to normal-paraffins ratio of 2.2 and boosted up cyclic content of 14%. Similarly the cyclic content in Blend 3 has been boosted up to around 15% but with narrow-cut jet fuel. Additionally, a Jet A-1 fuel was provided, to provide a reference to standard jet fuels in the market.

It is worth recording that the blends did not meet all requirements of an ASTM D7566 SPK; distillation slopes of Blends 1 and 3 were slightly narrower than the 22°C minimum for T_{90}-T_{10}. The fuel blends were deliberately selected to represent extremes of the generic FT approval in key areas such as distillation curve and lower density limits to add to the body of industry knowledge of chemical composition and combustion performance and assist in future specification setting efforts.

4. TEST METHODOLOGY

Throughout the development of a new engine type, or a new technology, it is normal practice to develop and derisk new designs via low-cost and low-risk methods at the outset, gradually building through to tests on more complex and realistic geometries and test facilities as the design matures. In support of its engine and technology development programs, Rolls-Royce owns, or has access to, a series of combustion and engine test facilities along the TRL road-map.

4.1 Test Rig

This test series took place on the TRL 3 SARS rig located within the Strategic Research Centre, Rolls-Royce, Derby. This facility provides test conditions at realistic ignition conditions from sea-level static to high altitude in-flight shutdown, see Figure 4.

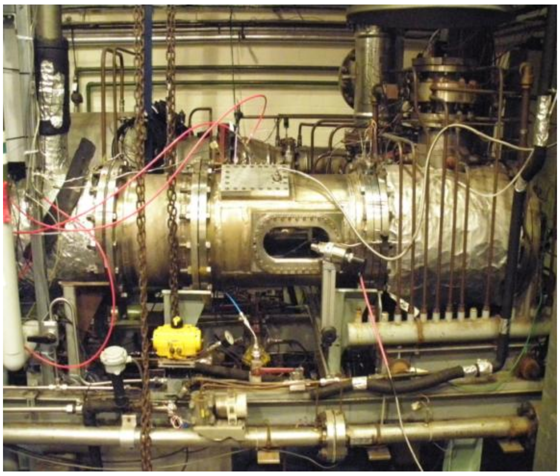

Figure 4 : Sub-Atmospheric Relight Sector rig, Strategic Research Centre, Rolls-Royce.

Air is drawn into and through the test rig by means of a vacuum pump, with automatically adjusted valves upstream and downstream of the test chamber. In conjunction with the vacuum pump, these valves control the pressure and mass flow rate of air through the test chamber. Mass flow rate is measured by use of vortex flow meters.

A temperature controlled refrigeration unit adjusts the temperature of the air such that the air temperature is consistent with the in-flight ignition condition being simulated. A water-cooled heat exchanger reduces the temperature of the test chamber exhaust before it passes through the vacuum pump to atmosphere.

The fuel supply also passes through a branch of the refrigeration unit so that it achieves a temperature commensurate with the ignition condition. This is normally higher than the air temperature since the fuel will be passing through an oil cooler on the engine and increasing in temperature. A schematic of the major flow paths in the test facility is shown in Figure 5.

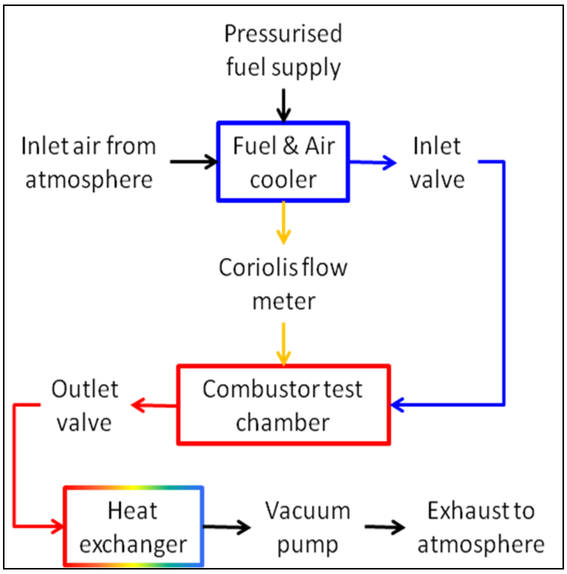

Figure 5 : Schematic of the flow paths through the SARS ring

Air mass flow rate and pressure are controlled to within ±0.01 lb s^{-1} and ±0.2psia of the required experiment set point by an automatic control system. Fuel flow rate is controlled to achieve the required FAR or equivalence ratio to within 0.001kg s^{-1} of the associated fuel mass flow rate by Rolls-Royce developed National Instrument LabView software and coriolis type flowmeters.

The test rig features optical access to the combustion test unit through a quartz window on the port side of the combustor. Ignition is detected either via a light intensity meter pointed into the test chamber, or by manual observation.

4.2 Combustor geometry

The combustor geometry is dominated by the combination of combustion liner and fuel injector. The combustor used for this research was an advanced co-axially staging lean burn fuel injector in a complementary lean burn combustion liner. This technology has been developed by Rolls-Royce through its advanced lean combustion system research programmes

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In common with all aerospace lean burn combustor designs, only the central "pilot" fuel circuit in the fuel injector is used during ignition. A cross-section of a similar injector design from a recent patent is given in Figure 6. The positions of the "pilot" and "main" flame regions have been indicated.

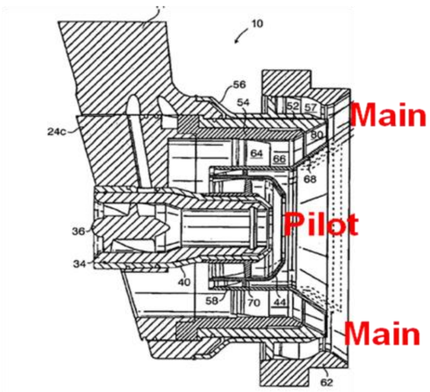

Figure 6 : Cross section of a similar fuel injector to that used in this experiment

In the TRL3 SARS rig, only 2 fuel injector sectors of the annular lean burn combustion liner can be fitted within the test chamber. In order to create a clean air optical pathway for the high speed diagnostic imaging reported in the complementary paper, only 1 fuel injector was fuelled for the ignition tests. The igniter was located in suitable position relative to the face of the fuel injector.

The use of only 1 of the possible 2 fuel injectors removed the ability to map the "light round" ignition region, i.e., where flame kernels from an ignited fuel injector propagate circumferentially around the annular combustor to injector positions which do not have a dedicated igniter. However, the benefits of improving the high speed diagnostic imaging offset this loss of data.

4.3 Test procedure

The objective of the test is to map the region on the W_{31} vs FAR plot within which successful and stable ignition is possible. The experiment necessarily also defines the regions where ignition is possible, but not stable, or where it is not possible. The simulated altitude ignition conditions at which all fuels were tested are given in Table 1.

In recognition of ignition being a stochastic process [4] and to keep facility occupancy and fuel use to a sensible level, the boundaries defining the successful and unsuccessful ignition regions are confirmed by obtaining 3 repeats of the same result. For the 8 possible outcomes of these 3 repeats with each result being either "Successful" or "Not Successful", it can be shown that the (non-)ignition probability at the (no-)ignition boundary is 80%

Test condition	Air pressure	Air temperature	Fuel temperature
	psia	K	K
1	6.0	265.0	288.0
2	8.0	278.0	288.0

Table 1 : Air and fuel set points during ignition testing at simulated altitude conditions

The test facility has a maximum fuel flow limit (to keep heat exchanger inlet temperatures below the equipment limit) which prevents the rich boundaries of the ignition regime from being mapped. Therefore, only the weak FAR extents of the ignition region were mapped during this programme.

The test procedure for each ignition point test is as shown in Figure 7. At each fixed air mass flow at the fixed air pressure and temperature condition, the test procedure is conducted until the lowest FAR at which successful ignition occurs 3 times is found, and the highest FAR (albeit a weaker FAR) at which unsuccessful ignition occurs 3 times is found.

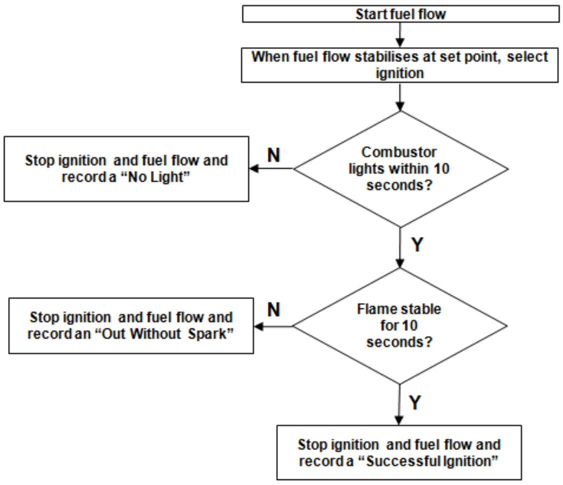

Figure 7 : Ignition point test procedure and result logic tree

With the fuel injector lit and stable at a fixed air mass flow, a weak extinction test is also performed. During this procedure, the LabView control system gradually decreases the fuel flow, and hence FAR, until the flame is extinguished.

These tests are then repeated at different mass flow rates until ignition is not possible at any FAR within the facility limits. The points indicating the limit of ignition, no ignition and weak extinction are then joined together to create the respective boundary. An example of the plotted results from such a test series is shown in Figure 8.

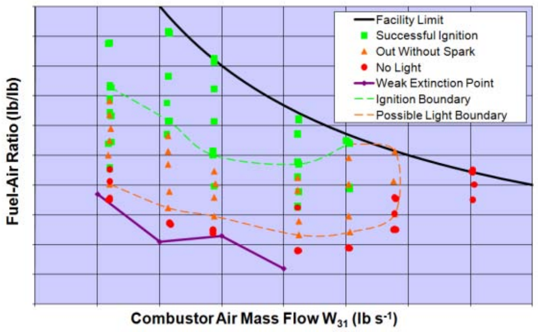

Figure 8 : Ignition test results with defined ignition boundaries

5. RESULTS

The altitude ignition experiments were conducted for five GTL fuel blends at two combustor inlet conditions. However, for the sake of brevity, only the results that highlight a significant impact on the performance are presented and discussed. First, the ignition boundaries such as successful ignition, possible light and the weak extinction limits of the GTL fuels are compared with the Jet A-1 fuel. Followed by, the effect of fuel chemical characteristics such as iso-to-normal paraffin ratio, cyclic carbon composition and the carbon range on altitude ignition performance is brought out by comparing the ignition results across the GTL fuels.

In all the presented figures in this text, the successful ignition is represented by a continuous line with filled square. The possible light and weak extinction limits are represented by a dashed line with filled triangle and cross marks respectively. The ignition results of the GTL fuels are distinguished from each other by using different colours. Furthermore, the results are plotted on a common (ordinate) scale to facilitate the comparison.

5.1 Gauge R&R analysis

Sections 5.2 through 5.5 will present and compare differences in the ignition and weak extinction boundaries between fuel types and composition. However, these comparisons must be made in the context of the gauge repeatability and reproducibility (GR&R) of the test method.

The following repeat experiments were performed to indicate the likely GR&R of the test method:

a. Repeat complete 6psi test with Jet A-1
b. Repeat boundary exploration at 6psi and $0.5W_{31norm}$ with CSPK2
c. Repeat boundary exploration at 8psi and $0.5W_{31norm}$ with CSPK2
d. Repeat boundary exploration at 8psi and $0.36W_{31norm}$ with Blend 2

The results of these experiments are summarised in Table 2, which shows the difference in the position of boundaries required in order to be confident that any differences are not simply a result of known experimental scatter.

Boundary type	Condition 1	Condition 2
Successful ignition Ψ	0.22	0.15
Maximum W_{31norm} for successful ignition	0.07	0.07
Possible light Ψ	0.07	0.01
Weak extinction Ψ	0.07	0.01

Table 2 : Measured experimental scatter in boundary positions

5.2 Comparison of Ignition boundaries

Figure 9 shows the comparison of ignition boundaries between CSPK1 and Jet A-1 fuels at (a) 6 psi and (b) 8 psi combustor inlet pressures. At 6 psi, the successful ignition envelope of CSPK1 is within the experimental scatter of that for Jet A-1. The weak extinction limit of CSPK1 is either fuel lean or the same as that of Jet A-1 when, $W_{31norm} < 0.45$. At high air mass flow ($W_{31norm} = 0.5$), the extinction limit shifts to a fuel rich condition in line with the ignition envelope.

At 8 psi, CSPK1 is able to successfully ignite at fuel lean and high air mass flow when compared to Jet A-1 fuel. As a result of extension of the successful ignition envelope towards fuel lean conditions, the possible light region is smaller than Jet A-1. At low air mass flow fuel lean ignition is possible with the former fuel. With an increase in air mass flow, the difference in fuel condition is seen to reduce. Interestingly, it is observed that with CSPK1 ignition is possible even at higher air mass flow than Jet A-1 fuel. The weak extinction limits of both the fuels are seen to exist at almost the same equivalence ratio at all combustor air mass flow conditions.

Both fuels tend to extend the ignition boundaries in the direction of high air mass flow (W_{31norm}) at 8 psi owing to higher combustor inlet pressure and temperature. This trend is observed for all fuels since this is result of the combustor conditions. CSPK1 and Blend-1 GTL fuels differ in their fuel composition by high iso-to-normal paraffin (I/N) ratio in the latter fuel. Since the ignition boundaries of Blend-1 are similar to CSPK1, the comparison of Blend-1 with Jet A-1 fuel is not discussed here.

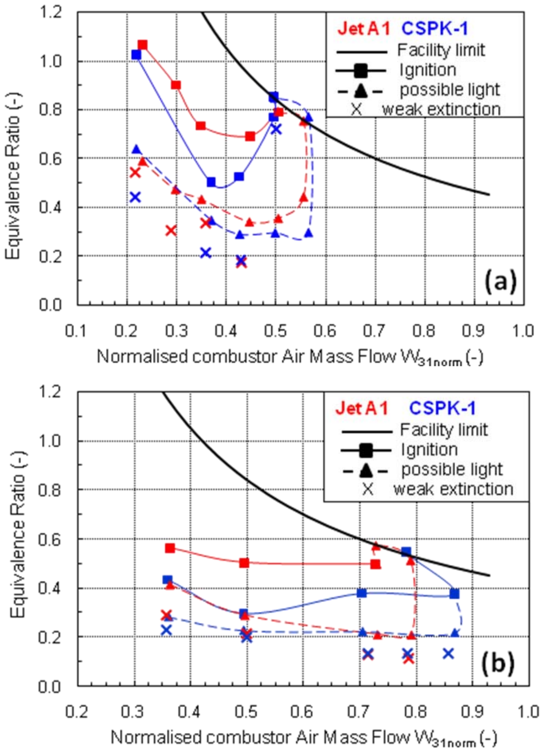

Figure 9 : Comparison of Ignition boundaries between Jet A-1 and CSPK1 GTL fuels at (a) 6 psi and (b) 8 psi combustor inlet pressures

Figure 10 compares the ignition boundaries between Jet A-1 and Blend-3 GTL fuels. Blend-3 is a fuel variant of CSPK1 with high cyclic carbon composition however, the I/N ratio of Blend-3 is the same as that of CSPK1 as shown in Figure 3.

With an increase in the cyclic carbon content of the fuel, the successful ignition boundary of Blend-3 shows a significant shift towards fuel lean conditions when compared to Jet A-1 fuel at 6psi and at some mass flows at 8psi. The shift observed with this fuel is significant when compared to other GTL fuels discussed earlier. In addition, at 8 psi, the successful ignition boundary is seen to extend to high combustor air mass flow than Jet A-1 in a way similar to that observed in CSPK1. However, there is insignificant difference in the possible light envelope when compared to Jet A-1 fuel at both the combustor inlet pressures. The weak extinction limits at 6 and 8 psi shows no significant difference compared to that of Jet A-1 fuel.

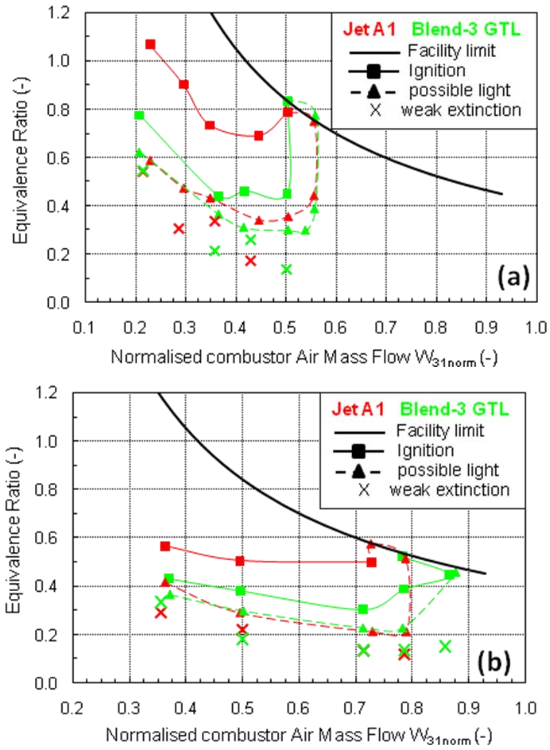

Figure 10 : Comparison of Ignition boundaries between Jet A-1 and Blend-3 GTL fuels at (a) 6 psi and (b) 8 psi combustor inlet pressures

So far, the ignition boundaries of fuels that differ from the base fuel in only one fuel characteristic are discussed. GTL fuels with more than one fuel characteristic different from the base fuel are also tested. These tests will bring out the combined effect of the fuel characteristics on the ignition performance. The ignition boundaries of Blend-2 differ from CSPK2 only marginally and hence the results that pertain to CSPK2 alone are presented in Figure 11 and discussed. Figure 3 clearly shows how the fuel characteristics of Blend-2 differ from CSPK2.

Considering the determined GR&R of the experimental method, the only significant differences in the ignition and weak extinction boundaries at 6psi of CSPK2 compared to Jet A-1 is weak extinction at a single W_{31norm} condition. On the other hand, with an increase in combustor inlet pressure to 8 psi, the ignition envelope shows a significant movement towards fuel lean side at high air mass flow.

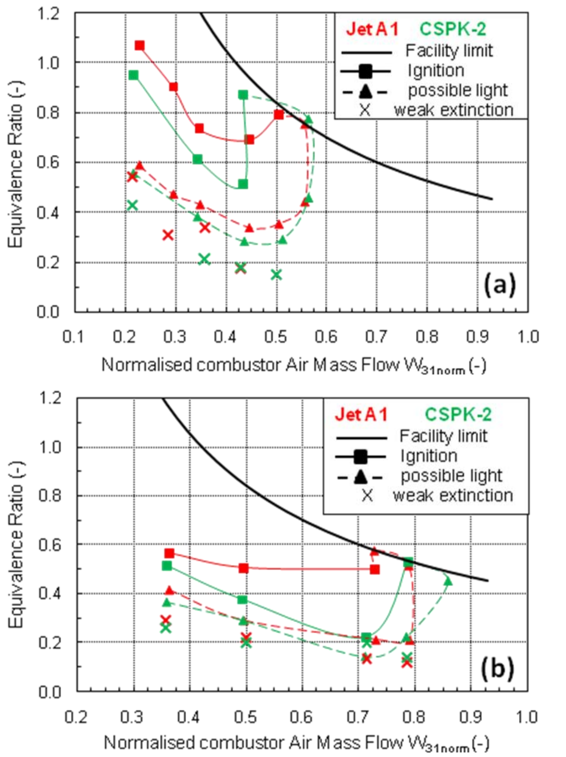

Figure 11 : Comparison of Ignition boundaries between Jet A-1 and CSPK2 fuels at (a) 6 psi and (b) 8 psi combustor inlet pressures

A summary of the ignition and weak performance of all fuels, as compared to Jet A-1, is given in Table 3 to Table 6. Values in **blue** indicate no significant change to datum Jet A-1, **green** values are significantly better for combustor performance (either higher mass flow or leaner equivalence ratio), while **red** values are significantly worse for combustor performance.

Fuel type	80% ignition probability point at 0.5 W_{31norm}	Highest W_{31norm} for successful ignition boundary
Jet A-1	0.691	0.50
CSPK1	0.503	0.50
CSPK2	0.491	0.43
Blend 1	0.502	0.51
Blend 2	0.584	0.50
Blend 3	0.446	0.50

Table 3 : Summary of ignition boundary findings at condition 1

Fuel type	Weak extinction Ψ at 0.21 W_{31norm}	Weak extinction Ψ at 0.42 W_{31norm}
Jet A-1	0.543	0.176
CSPK1	0.425	0.176
CSPK2	0.411	0.176
Blend 1	0.587	0.176
Blend 2	0.513	0.191
Blend 3	0.528	0.249

Table 4 : Summary of weak extinction boundary findings at condition 1

Fuel type	80% ignition probability point at 0.5 W_{31norm}	Highest W_{31norm} for successful ignition boundary
Jet A-1	0.506	0.73
CSPK1	0.285	0.87
CSPK2	0.362	0.79
Blend 1	0.421	0.76
Blend 2	0.295	0.73
Blend 3	0.370	0.87

Table 5 : Summary of ignition boundary findings at condition 2

Fuel type	Weak extinction Ψ at 0.36 W_{31norm}	Weak extinction Ψ at 0.71 W_{31norm}
Jet A-1	0.293	0.132
CSPK1	0.220	0.132
CSPK2	0.249	0.191
Blend 1	0.264	0.132
Blend 2	0.249	0.147
Blend 3	0.323	0.132

Table 6 : Summary of weak extinction boundary findings at condition 2

In this section, so far, the ignition boundaries of different GTL fuels are individually compared with the ignition boundaries of regular Jet A-1 fuel. While some of the differences identified are statistically significant from a combustor operability viewpoint, it is expected that these could be overcome at a whole engine design level.

In order to highlight the effect of fuel characteristics on the relight performance, it is essential that the ignition boundaries of GTL fuels with different fuel characteristics are compared with each other and it is discussed next.

5.3 Effect of Iso-to-normal paraffin ratio

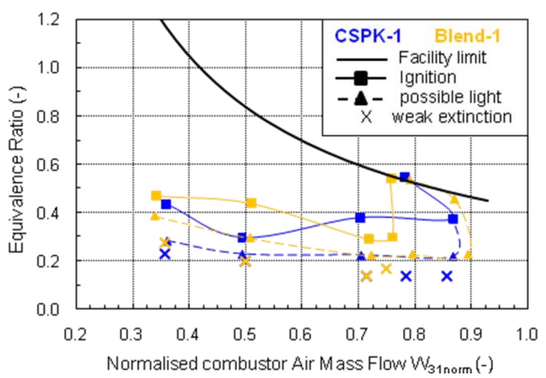

Figure 12 : Comparison of the ignition boundaries between CSPK1 and Blend-1 GTL fuels at 8 psi combustor inlet pressure

Figure 12 shows the influence of iso-to-normal paraffin (I/N) ratio on the ignition performance at 8 psi. At 6psi combustor inlet condition, there is no difference between CSPK1 and Blend-1 and hence the comparison is not shown here. In Figure 12, with CSPK1, the maximum W_{31norm} at which ignition is possible is increased. In the weak extinction limit, I/N ratio seems to have minimal effect.

5.4 Effect of cyclic carbon content

Here, the ignition performance of GTL fuels with different cyclic carbon content in the fuel specification is compared. First, the fuels having low iso-to-normal paraffin ratio is compared. Followed by, the ignition performance of fuels with high I/N ratio in conjunction with wide carbon cut is compared.

Figure 13 shows the effect of cyclic carbon content on the ignition perfomance at 6 psi combustor inlet pressure. At 6 psi, there is improved ignition performance at weak conditions only at the low and high ends of the W_{31norm} range considered. With high cyclic carbon, the weak extinction limits are fuel rich (up to W_{31norm} = 0.43) when compared to CSPK1. However, the point at W_{31norm} = 0.5 suggest that at high air mass flow, fuel lean, weak extinction is possible with high cyclic carbon content.

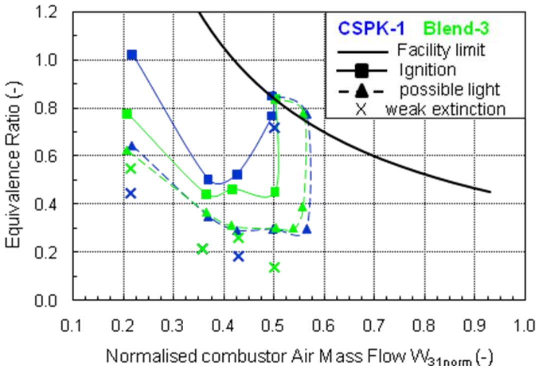

Figure 13 : Comparison of the ignition boundaries of CSPK1 and Blend-3 GTL fuels at 6 psi combustor inlet pressure

The influence of cyclic carbon content in conjunction with high I/N ratio on ignition performance with wide carbon cut fuels is shown in Figure 14. At 6 psi, there is no change to the successful ignition envelope. The possible light regions are also unchanged between the fuels. The weak extinction limit at low combustor air mass flow, $W_{31norm} \approx 0.22$, is fuel lean with low cyclic carbon content. Interestingly, this effect is consistent and observed in narrow carbon range fuels (refer Figure 13) as well. With an increase in combustor air mass flow, the difference in the extinction limits diminish until W_{31norm} = 0.5. The CSPK2 weak extinction point at the maximum inlet air mass flow (W_{31norm} = 0.5) can be disregarded since this was taken following a single successful light in the possible light region for this fuel and successful ignition is not guaranteed at this condition.

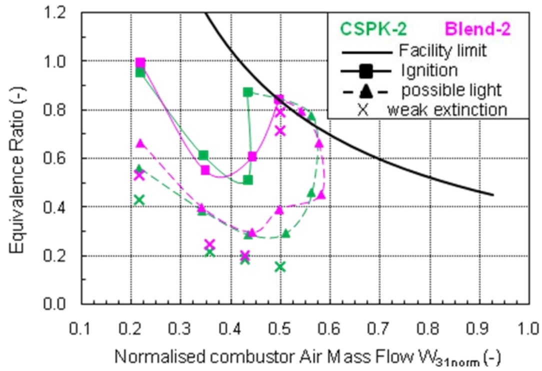

Figure 14 : Comparison of the ignition boundaries between CSPK2 and Blend-2 GTL fuels at 6 psi combustor inlet pressure

5.5 Effect of Carbon range

Here, the role of carbon range such as narrow carbon cut, CSPK1 GTL and the wide carbon cut, CSPK2 GTL (refer Figure 3) on the ignition performance is discussed. A one-on-one comparison between these fuels is difficult since it was not possible to change the carbon range characteristic alone without altering other fuel characteristics using the available commercial solvents used in the blending. Nevertheless, it is expected that these results will assist to draw qualitative inferences between the two carbon range fuels.

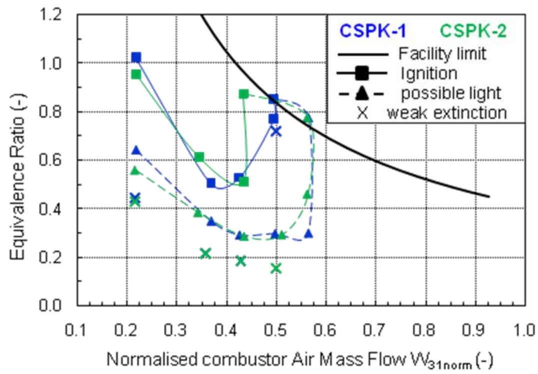

Figure 15 : Comparison of the ignition boundaries between CSPK1 and CSPK2 GTL fuels at 6 psi combustor inlet pressure

Figure 15 shows the comparison of ignition boundaries of GTL fuels with different carbon content at 6 psi. Here, there is no change in the successful ignition envelope or weak extinction regimes between fuels. The comparison of ignition loops at 8 psi is not show here for the sake of brevity. However, the trends can be infered by comparing Figure 9 and Figure 11.

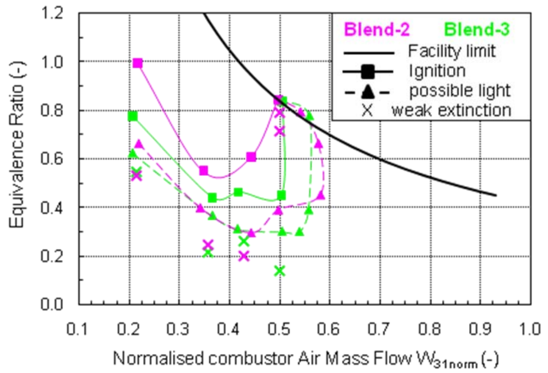

Figure 16 : Comparison of the ignition boundaries between Blend-2 and Blend-3 GTL fuels at 6 psi combustor inlet pressure

Figure 16 shows the comparison of ignition boundaries of GTL fuels with different carbon range in conjunction with I/N ratio at low combustor inlet pressure. At 6 psi inlet condition, the increase in carbon range is seen to have a negative effect on the successful ignition boundary, but this is only significant at the high mass flow point. Since the cyclic carbon content of both the fuels are the same, this negative effect could be due to the combined influence of carbon range and the I/N ratio. However, from Figure 14 it is shown that the successful ignition envelope of CSPK2 and Blend-2 are very close to each other and from Figure 15, Blend-2 is indistinguishable from CSPK1. Hence, it is possible that the adverse effect on successful ignition envelope of Blend-2 in Figure 16 could solely be due to the carbon range and not due to I/N ratio.

The weak extinction limits of the fuels at 6 psi are closely distributed except at the maximum air mass flow condition, where the weaker extent of the ignition envelope facilitates a lower equivalence ratio for weak extinction.

6. CONCLUSION

In this work, the altitude ignition performance of five GTL synthetic fuels and conventional Jet A-1 fuel were experimentally investigated. The experiments were carried out at two combustor inlet pressures which represent the combustor inlet conditions at approximately, 25,000 to 30,000 ft altitude using the Rolls-Royce plc TRL3 sub-atmospheric altitude ignition facility in Derby, UK. The key conclusions of this work are as follows:

1) None of the GTL fuels have shown any significant deterioration on the ignition performance when compared to the regular Jet A-1 fuel which could not, in theory, be managed at a whole engine design level.
2) Low iso-to-normal paraffin ratio fuels indicate improved ignition performance in terms of W_{31norm} i.e., the air velocity limited part of the ignition envelope. It is recommended that this be further investigated and confirmed on higher TRL facilities.
3) Variations in ignition loops at 8psi tend, in general, to be less apparent at 6psi, suggesting that at these conditions, fuel chemistry and composition is not always the rate determining step.
4) The carbon cut seems to have influence on the successful ignition performance only with high cyclic content of GTL fuels

Further experimental work on the fuels detailed herein, specifically ignition delay time, generation and validation of full and reduced reaction mechanisms, and spray characteristics are underway at other research establishments under this programme. It is expected that this data, once available, will produce further insight into the results detailed here.

7. ACKNOWLEDGEMENTS

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