ITAKA

Collaborative Project

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D4.3 Emissions report and database of systems key performance parameters (T7.2.2B MCA batch)

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Executive summary

In the development of alternative fuels for aviation there have been a number of significant scale research projects within the EU: SWAFEA (2008-2011) investigated the impact and feasibility of using alternative fuels in aviation; Alfabird (2009-2012) evaluated a selection of ‘best candidate’ alternative fuels; and most recently ITAKA (2012-2015) an intermediate scale ‘value chain’ project that aims to produce, flight-test and evaluate 4000 tonnes of sustainable biofuels.

The Initiative Towards sustAinable Kerosene for Aviation (ITAKA) project is a collaborative research venture designed to address some of the barriers that challenge the development of sustainable aviation biofuels in the EU. In the following task, the direct emissions from the combustion of the ITAKA MCA batch biofuel in a small gas turbine engine are assessed so that their environmental impact can be placed in context and better understood. This is an important issue since aviation emissions can have a direct impact on atmospheric chemistry and on the radiative balance that extends well beyond the CO_2 effect: Contrails formed by condensation of water vapour onto exhaust PM and aerosols may trigger the formation of induced cirrus clouds, similarly, emissions of NO_x may perturb the natural chemical cycles and lead to ozone production or destruction depending on latitude and altitude as well as modifying the time of residence for methane in the atmosphere. Hence, modelling the atmospheric impact of aviation requires the synthesis of aircraft movement data and detailed aircraft emissions data into atmospheric models. And whilst the combustion of fuel in a gas turbine engine is a highly efficient process, there is no reason to assume that the emissions from HEFA based fuels will be identical to those from the combustion of Jet A-1. Due diligence requires that the emission profile for the combustion of these fuels must come under scientific scrutiny ahead of the large scale introduction of new fuels on climate, security or economic grounds.

The ITAKA HEFA based biofuels are produced with properties that are within the specification envelope of ASTM D7566, however there are appreciable chemical and physical differences. The impact of these differences on aircraft emissions is largely unknown, although some consensus and generalized rules are beginning to emerge. The objective of this task has been to collect experimental emission data using a small APU gas turbine engine and consolidate this with structured knowledge from the wider literature. In comparison to full rig testing or on-wing testing, emission testing on an APU has the advantage that a comparatively modest quantity of fuel is required, tests are relatively low cost, and the information gained is comparable since fuel chemistry is the dominant impact parameter.

The experimental data capture the important emission characteristics and key features of engine performance when powered by ITAKA MCA HEFA based biofuel. A full range of fuel blend ratios has been considered from 100% Jet A-1 through to 100% biofuel. This is the largest most comprehensive dataset in the literature. It has been extended to cover the range of blends beyond the current ASTM 50% certification limit which may be important in future certification, and allows performance and emission trends to be assessed with statistically significant confidence.

The ITAKA MCA biofuel sourced from SkyNRG was derived from used cooking oil, whilst a straight run Jet A-1 sourced from within the UK was used as both baseline and blend component fuel. A complete GC x GC analysis of the MCA biofuel and baseline Jet A-1 provided a comprehensive qualitative and quantitative chemical breakdown of the fuel groupings, and showed that the aromatic, alkane and cyclo-paraffinic structures in the two fuels are significantly different.

Key outcomes and conclusions are:

- The engine performance data showed a reduction in fuel flow with increasing biofuel blend fraction. The reduction in fuel flow scales in proportion to the mass corrected specific energy density of the fuel blend that enters the engine. This is consistent with flight performance data reported in ITAKA deliverable D4.1.
- A marginal drop in EGT and a slight reduction in engine shaft speed were also observed with increasing biofuel blend ratio. These trends are statistically significant. However, the author is not aware of any data within the literature that supports this observation and further analysis is necessary.
- For particulate emissions, a clear and pronounced reduction in the SAE smoke number was observed with increasing biofuel blend ratio. The reduction in smoke number with blend ratio was linear to a good first approximation, and the rate of reduction with blend ratio was approximately the same for all engine conditions. The data are consistent with the consensus opinion that smoke number primarily scales with the aromatic content of the fuel.
- A full characterisation of the nvPM component of the smoke has also been developed using the state of the art North American Reference System. These data showed that to a first approximation both the number and mass based emission indices reduce almost linearly with increasing MCA blend fraction (although there is some evidence of asymptotic behaviour in the mass based emission index at fuel blend ratios >80%). The magnitude of these reductions are greatest for higher engine powers: with a 52% reduction in PM mass and a 38% reduction in PM number with 50% blended MCA / Jet A-1 fuel, rising to a 93% reduction in PM mass and a 74% reduction in PM number with 100% MCA fuel. These reductions are accompanied by a corresponding shift in the geometric mean diameter to smaller size, and an increasingly mono-disperse size distribution.
- For gaseous emissions, no statistically significant change in the emissions of NOx or UHC was observed with increasing MCA blend fraction on this hardware (although the trend line does imply the hidden presence of a small reduction). In contrast a small but statistically significant reduction in CO was observed with increasing MCA biofuel fraction. These data are consistent with the range of data reported elsewhere and illustrate the relatively small scale perturbation in the emission of these gaseous species that is expected.

The study wraps up with a discussion section that places the ITAKA experimental emissions data into context with a synthesis of structured knowledge from the literature and past studies. No adverse effects were detected with the use of the ITAKA MCA batch biofuel at any blend ratio including those above the 50% certification limit.

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Abbreviations

AEM	Advanced Emission Model
AFR	Air Fuel Ratio
APU	Auxiliary Power Unit
ARP	Aerospace recommended practice
ASTM	American Society for Testing and Materials (now ASTM International)
CAAFI	Commercial Aviation Alternative Fuels Initiative
CO	Carbon monoxide
CO_2	Carbon Dioxide
CTL	Coal To Liquid
EASA	European Aviation Safety Authority
EGT	Exhaust Gas Temperature
EI	Emission Index
FT	Fischer Tropsch
GHG	Green House Gas
GTL	Gas To Liquid
HEFA	Hydrogenated esters and fatty acids
H/C	Hydrogen to Carbon ratio
HRJ	Hydro-treated Renewable Jet
LAQ	Local Air Quality
N_2	Nitrogen gas
nvPM	non-volatile Particulate Matter
NOx	Nitrogen Oxides (NO + NO_2)
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers (now SAE International)
SAMPLE	Studying sAmpling and Measuring of aircraft ParticuLate Emissions
SN	Smoke Number
UCO	Used Cooking Oil
UHC	Unburned Hydrocarbons

Definitions

Emission Index (EI) is defined as the mass of a given pollutant emitted per unit mass of fuel burned, units are therefore g/kg fuel. However, within this text it is necessary to include a tighter definition with units of ‘g/kg Jet A-1’ and ‘g/kg Jet A-1 equivalent’ to allow the comparison of fuels. The later equivalent EI is scaled by the fuel flow ratio.

NOx is a generic term defined as the total concentration of both NO (Nitrogen monoxide) and NO_2 (Nitrogen dioxide).

nvPM is the carbonaceous non-volatile particulate matter component in the emissions. In other texts it may also be referred to as ‘soot’ or ‘elemental carbon’. Currently a formal and universally accepted definition of nvPM is lacking. In this text, the definition is equivalent to that given in SAE AIR 6241.

GC X GC is a two-dimensional gas chromatography and is extensively applied to the analysis of complex oil samples to determine the many different types of Hydrocarbons and isomers.

1 Introduction

Security of supply and growing environmental concerns are placing increasing pressure on the transport sector to diversify away from petroleum derived fuels. In the European Union, Directives are in place to encourage fuel source diversification and the production of fuels refined from renewable feedstocks. The most recent Directive [EU Directive 2009/28/EC] specifies that at least 10% of the energy used in each member state's transport sector must come from renewable resources by 2020. This directive was introduced to amend concerns that targets specified in the previous Directive [EU Directive 2003/30/EC] were damaging the environment and causing social issues [Harrabin 2008]. Currently aviation is not mandated within this directive, but it is contextually indicative of the pressure the aviation sector faces to reduce its GHG emissions and secure a sustainable future.

Within the aviation sector, the development and certification of alternative drop-in fuels are progressing at a rapid pace: a standard specification for aviation fuel containing a 50% blend of Fischer Tropsch (FT) synthesized hydrocarbons was approved by ASTM in 2009, Hydrogenated esters and fatty acids (HEFA), previously referred to as Hydro-treated Renewable Jet (HRJ), qualified as a 50% blend with petroleum Jet A-1 in 2011, and the Synthetic Iso-paraffin (SIP) pathway qualified for use as a 10% blend with Jet A-1 in 2014 [ASTM D-7566-14a]. In support of the certification process, more than 1500 demonstration flights of commercial aircraft burning various blends of Jet A-1 and either biomass or FT fuels have also been conducted [see for example Blakey et al 2011].

Fischer Tropsch fuels such as gas-to-liquid (GTL) and coal-to-liquid (CTL) can offer security of supply, however, in a full 'well to wake' environmental analysis the greenhouse gas (GHG) emissions from the combustion of these fuels do exceed the equivalent emissions from the use of conventional jet fuel [Stratton et al 2010]. Nevertheless, the economics of production for GTL and CTL are favourable at current and predicted future oil prices [Crooks 2009]. The perceived opportunity for these fuels is as an effective mechanism to dampen price volatility in the jet fuel supply market [Vera-Morales 2009], although other authors argue that these fuels will have a limited effect on price volatility over the near term [Hileman et al 2009]. Second generation alternative jet fuels such as HEFAs produced from renewable sources have reduced life cycle GHG emissions relative to petroleum based jet fuel [Stratton et al 2010]. In the future HEFA fuels could play a central role within a basket of measures to help mitigate aviation's contribution to climate change [Aviation and alternative fuels (a), (b)]. There are however many significant challenges that must be overcome before second generation alternative fuels are economically viable and widely available [Aviation and alternative fuels (c), (d)].

The overall combustion of fuel in a gas turbine engine is a highly efficient process. Nevertheless, there is no reason to assume that the emissions from the combustion of alternative drop-in fuels in gas turbine engines will be identical to those from the combustion of Jet A-1. Accordingly the introduction and use of alternative fuels in aviation may bring with them a shift in emphasis for the priority pollutant compounds in the emissions. As such, due diligence must require that changes in the emission profile for the combustion of alternative fuels in terms of non-CO_2 effects must come under scientific scrutiny ahead of the large scale introduction of new fuels on climate, sustainability or economic grounds.

The sustainable biofuels produced and used within the ITAKA project are both HEFA derived biofuels but differ in the feedstock on which they are based: The first biofuel, referred to as the MCA batch, was derived from a used cooking oil (UCO) feedstock imported from the USA (200 Tonnes, with RSB & EPA sustainability certification), whereas the second biofuel was derived from a Camelina vegetable oil feedstock mostly grown in Spain (885 Tonnes, with RSB & EPA sustainability certification) but augmented with a supply imported from the USA (440 Tonnes / EPA sustainability certification).

To characterise the performance and emissions from the ITAKA biofuel on a representative range of commercial engine hardware would be an almost impossible task, and prohibitively expensive: there are over 500 engines listed in the ICAO engine emissions databank and so a large number of rig tests would be required. Furthermore, the differences in performance and emissions from most modern engines are comparatively modest and converging. In contrast, fuel chemistry has a much greater impact on emissions, and to explore the effect a shift in fuel chemistry might convey requires just one representative engine and it can be quite small.

The purpose of this task was to specifically characterise the emission of the MCA batch ITAKA biofuel blends in a gas turbine relative to the emission from Jet A-1. The emission characteristics from the Camelina batch ITAKA biofuel will be reported separately in a sister deliverable. An APU gas turbine was selected as appropriately scaled demonstrator hardware, such that the scope of the test programme corresponds to intermediate scale combustion trials that fit into the range of possible analysis between laboratory bench scale testing of fuels (requiring ~ 1 litre of fuel) and full engine tests (requiring ~ 10,000 litres of fuel).

Within this report, the experimental procedure and measurement instrumentation are outlined in Chapter 2, the zero cost and additional subtasks that have been included in the program are described in Chapter 3, the engine performance data is given in Chapter 4, the emission characterisation of the MCA batch biofuels is discussed in Chapters 5, a discussion of the data in relation to existing knowledge is given in Chapter 6, and conclusions to be drawn are given in Chapter 7. A cautious extrapolation of these data to overall fleet emissions is given in separate ITAKA deliverable.

2 Experimental: Engine, fuel and instrumentation

In the following section experimental details of the APU test bed facility, the sampling probes, the operating procedure, the fuels under test, and measurement instrumentation are given. All experimental data was collect at the APU test bed facility at the Low Carbon Combustion Centre, Rotherham, UK in June 2014.

The auxiliary power unit engine

The properties and characteristics of the chemical species emitted in the exhaust from a gas turbine engine are dependent upon the fuel chemistry and the design of the engine hardware (particularly the combustor). However reliable modeling of combustion and exhaust emissions is not currently possible, and ICAO is reliant upon the maintenance of an emissions database for each individual engine type that has been derived from measurement data. Equally, modeling across the database to infer and predict consistent emission characteristics is similarly non trivial, although some general rules do apply. The APU engine used in this task is representative of gas turbine technology, though a degree of caution is required in extrapolating emissions data across the fleet in any precision beyond generality. It is nevertheless as appropriate as any other gas turbine engine but is considerably more manageable and cheaper to operate than full rig testing.

The exhaust emissions from the combustion of the ITAKA biofuels were characterised using used a Garrett Honeywell GTCP85 -129 gas turbine engine. The Garrett Honeywell GTCP85 gas turbine engine is an auxiliary power unit (APU) representative of relatively modern technology and originated from a British Airways B737.

The engine management system controls to a fixed shaft speed and the engine operating conditions is set by changing the bleed air flow. The APU also houses a 32 KW generator, however it is not possible to change the engine operating conditions by loading this generator, since the overall power generated by the APU is substantially higher and no significant change in fuel flow or exhaust gas temperature is observed when the generator is loaded.

Measurements of the emission characteristics and engine performance data were recorded when powered by conventional Jet A-1 and a number of different Jet A-1 / ITAKA biofuel blend ratios. The different fuel blends were mixed in house from a combination of the neat 100% ITAKA fuel supplied by SkyNRG and a standard Jet A-1. Detailed certificates of quality for these fuels are shown in annex A. The Jet A-1 aviation kerosene was sourced locally in the UK and was used for all of the experimental work. As such, all results are referenced to this baseline.

Three standard APU power setting were used throughout as defined below:

- No Load (NL): This is the lowest power setting equivalent to idle. Fuel flow for this condition is approximately 18 g s^{-1} for Jet A-1. The operator has no mechanism to manipulate this power setting and control of this condition is set by the engine management system and so is highly repeatable. On an aircraft this power setting is used during the “APU Start” mode.
- Environmental Control System (ECS): This is a mid power setting and fuel flow for this condition is approximately 26 g s^{-1} for Jet A-1. Control of this condition is set by the engine management system in response to the opening of the environmental bleed valve and so is highly repeatable.

The operator has no mechanism to manipulate this this power setting. On an aircraft this is the normal running condition used to support the “Gate In” and “Gate Out” modes.

- Main Engine Start (MES): This is the highest power setting and fuel flow for this condition is approximately 32 g s^{-1} for Jet A-1. Control of this condition is set by the engine management system in response to the operator opening of the engine bleed valve. In this case the operator can manipulate the power setting through control of the variable engine bleed valve. For the work discussed herein, a repeatable engine condition is achieved through adjustment of this bleed valve in order to achieve a fixed and predetermined exhaust gas temperature (EGT). On an aircraft this engine condition is used to support the start of the main engines.

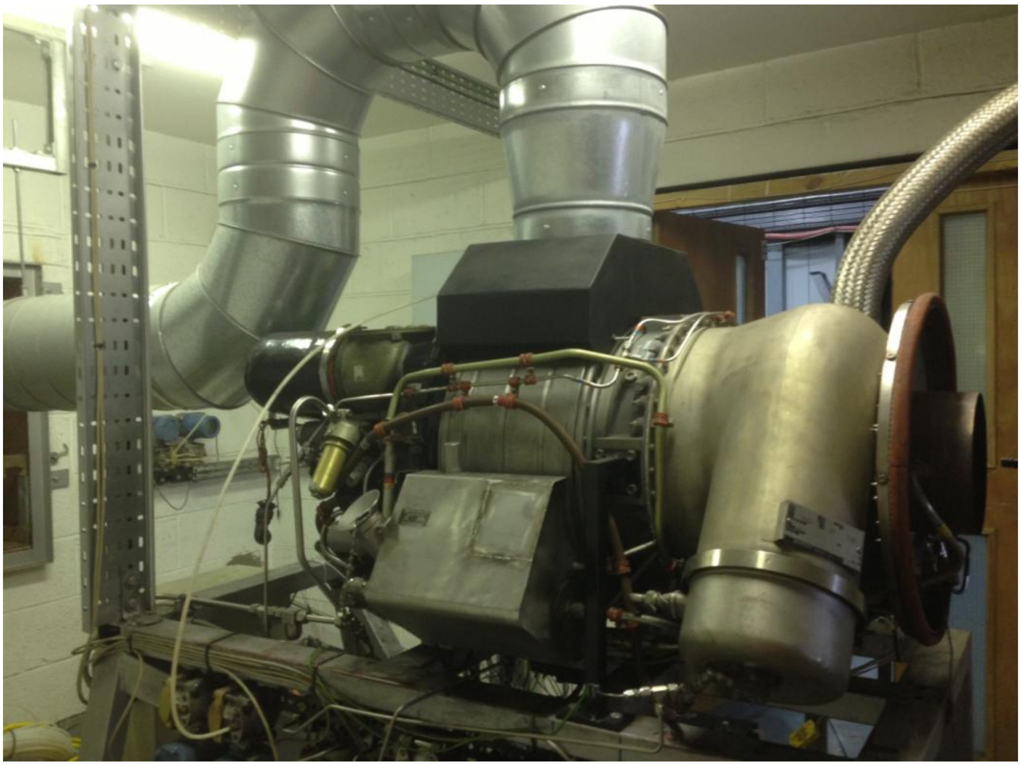

Figure 1. Photograph of Garrett Honeywell GTCP85 APU gas turbine engine used in the ITAKA emission test program.

The engine operational parameters taken as an average over four cycles with Jet A-1 are shown in Table 1. The increase in the attendant uncertainty for the MES engine condition is reflective of it being an operator set condition.

Engine Parameter	APU Operating Condition		
	NL	ECS	MES
Fuel flow rate (g/s)	17.8 ± 0.2	25.9 ± 0.2	31.8 ± 0.4
AFR	135.9 ± 3.9	84.4 ± 0.8	62.2 ± 1.0
EGT (ºC)	323.0 ± 3.7	475.8 ± 4.6	604.3 ± 6.2

Table 1. Garret Honeywell GTCP85 typical engine operational parameters with Jet A-1.

Fuels

The ITAKA MCA batch biofuel is a neat 100% UCO derived kerosene, sourced from SkyNRG, and shipped from Rotterdam to Sheffield in May 2014. This fuel is slightly ‘out of specification’ in that it contains a concentration of aromatics (~ 1.4% by mass) that is greater than allowed under the ASTM D7566 specification, which sets an upper limit of 0.5% by mass. This upper limit in the ASTM specification is not specifically related to concerns about the fuel aromatic content per say, but is instead a surrogate measurement to ensure that the feedstock oil has been sufficiently hydro-treated so as to warrant the complete removal of any heteroatoms that may have been previously present (plant oils ordinarily contain many heteroatoms such as N, O, Na, K, P, amongst others). The removal of heteroatoms to produce a pure hydrocarbon fuel ensures consistency of product and is an essential criterion for the safe operation of aircraft. Consequently, the MCA fuel batch does not fully meet the ASTM D7566 specification and should (strictly) be re-hydrotreated to reduce the aromatic content to below 0.5% before blending with Jet A-1 to achieve an aromatic content in the range 8% to 25%. However in this task, the use of biofuel that is slightly out-of-specification is not detrimental to the overall output of the study since the test bed engine is not subject to flight safety criteria and the unknown chemical components have been defined from a rigorous analytical approach. The more significant and critical criteria is that all emission measurements are made relative to a known and defined Jet A-1 baseline; measurements on a slightly out of specification biofuel of known properties is more informative than measurements of emissions from a blended fuel that contained a Jet A-1 of unknown characteristics. It is because of this later requirement that the stock of secondary-hydrotreated MCA batch biofuel pre-blended with Jet A-1 in a 20% ratio and used in the KLM flight test was unsuitable for this task.

Consideration of the original Intertek certification report for the MCA batch biofuel showed the hydrocarbon composition measured by ASTM D5291 to be 98.05% (in comparison to a specification minimum of 99.5%). The mass balance comparison between the hydrocarbon and non-hydrocarbon fuel composition does not account for this difference. Consequently there is a lack of clarity in the understanding of the overall makeup of this fuel and further lab analysis was required in order to put the emissions data into clear context (detailed later). Furthermore, some insight into the uncertainty associated with the standard methods of fuel analysis can be gained from the comparison of data: The concentration of aromatics in the MCA batch biofuel was determined by Intertek (Netherlands) to be 1.4% by mass using method D2425; whereas the concentration of aromatics in the same MCA batch biofuel was determined by Intertek (UK) 1.8%

by volume using method IP156 (see annex A). These data remain inconsistent even after differences in density are accounted for.

Table 2 gives a summary of selected fuel properties for the MCA batch of fuel and in comparison to the standard blend Jet A-1 feedstock that was used in the emissions testing (Note. Both sets of data come from Intertek (UK) who analysed the two different fuels back to back, so the inter-lab variation previously noted should be a minimum). It is important to note the significant difference in density between the two fuels, with the consequence that the specific energy for the MCA fuel is appreciably greater on a mass basis and appreciably lower on a volume basis. It is therefore reasonable to expect that fuel flow to the engine, which is conventionally measured in mass per unit time, will decrease with increasing biofuel blend ratio.

Fuel	Jet A-1 blend feedstock	ITAKA MCA batch
Density (kg/m3)	805.3	759.6
Method	IP365 Density at 15°C	IP365 Density at 15°C
Specific energy (MJ/kg)	43.153	44.023
Method	D3338 (S Corrected)	D3338 (S Corrected)
Specific energy (MJ/l)	34.75	33.44
Aromatics (% Vol)	19.2	1.8
Method	IP156 FIA	IP156 FIA
Sulphur (% mass)	0.033	<0.003
Method	D4294 Sulphur	D4294 Sulphur
H/C ratio	1.89	2.14
Method	D5291	D5291
Smoke point (mm)	23.0	>50
Method	D1322	D1322
Kinematic viscosity at -20 C (cSt)	3.521	3.80
Method	IP71	IP71

Table 2. Selected fuel properties for ITAKA MCA batch biofuel and the Jet A-1 blend (a detailed and independent third party analysis of these fuels can be seen in annex A).

The MCA fuel was delivered and stored in lacquer lined drums throughout as traces of iron can detrimentally affect the thermal stability and this effect is exasperated by the high volume to contacting surface area that is present with standard steel drums. The standard reference Jet A-1 was stored in a single dedicated 10,000 litre stainless steel fuel store.

Each of the fuel blends to be tested was formulated in house through careful weighing and mixing from the MCA batch biofuel supplied by SkyNRG and the reference Jet A-1. A GC x GC chemical analysis of both the MCA batch fuel and reference Jet A-1 was used to quantify what was expected qualitatively and show that the aromatic and cyclo-paraffinic structures in the two fuels are very significantly different (see annex 2).

In total approximately 18 different fuel blend emission tests were run as part of the ITAKA project, these were interspersed with additional baseline measurements made as necessary depending upon measurement drift, measurement uncertainty, and changes in the prevailing ambient conditions. As a mitigation measure to minimize drop out in the dataset from instrument failure or difficulties with systematic drift, the scheduling of the different fuel blends to be tested was 'interlaced' over the experimental campaign such that emissions from a wide range of different fuel blends were measured on each and every day.

Note. As a part of the ITAKA project, KLM has been operating a commercial service fueled by a secondary-hydrotreated derivative of the above MCA batch biofuel blended with Jet A-1 in a 20% ratio. Whilst it would have been highly desirable to assess the emissions from this blended and ASTM certified fuel at one or two specific test points to cross check that the characterization curves for the 'off-spec' MCA batch fuel are within bounds, unfortunately this was not possible and the ASTM certified fuel as used by KLM could not be made available by SkyNRG due to logistical difficulties.

Standard measurement instrumentation

Standard instrumentation for the measurement of the four ICAO engine database species NOx, CO, UHC and smoke number (SN) are as follows:

CO_2 detector (Sable Systems model CA-2A). Used to monitor CO_2 concentrations in the sample line to establish dilution factors and calculate emission indices.

Signal 3000 Flame Ionization Detector (FID). Used to measure the concentration of total unburned hydrocarbon in the emissions. Required operational, span and zero gases: H2 (40%) balance He (FID fuel); C3H8 balance synthetic air (FID span); Synthetic Air (FID zero).

Eco Physics Chemi-Luminescence Analyser (CLA). A dual channel NO_X (NO and NO_2) analyzer. Required operational, span and zero gases: NO balance nitrogen (CLA span); Nitrogen (CLA zero)

Binos Non Dispersive Infrared Sensor (NDIR). Dual channel CO and CO_2 analyzer – principle: non dispersive infrared sensor. Required operational, span and zero gases: CO and CO_2 balance nitrogen (NDIR span); Nitrogen (NDIR zero)

Richard Oliver (SAE) Smoke Number Measurement. Operates on the principle of a change in the reflectance value of Whatman No. 4 filter paper (as per ARP procedure).

High volume sampler for gravimetric analysis. A 300 litre/minute high volume pump was used to draw exhaust gases through a pair of glass fibre filters positioned in tandem (primary collector and a secondary backup collector). The gravimetric analysis provides off-line data on the mass loading of particulate matter in the exhaust and can also be analysed for trace chemical species such as PAH.

The sampling probes

Two identical single point sampling probes in the exit plane of the gas turbine positioned at a distance of less than ½ a nozzle diameter and almost collocated were used to collect emission samples: the first line was dedicated to the collection of exhaust emissions for the nvPM measurement work (upper probe) whilst the second was dedicated to the measurement of ICAO specified gases and smoke number (lower probe). Carbon dioxide was measured in both lines for the calculation of dilution factors. The two probes were positioned to the left of exhaust centre line as shown in Figure 2. As an indicator of scale the exhaust exit of the APU is 20 cm in diameter. Other probes structures in the centre and right of centre of the figure are engine management sensors. The heated line from the ICAO probe was maintained at a temperature of 160° C in accordance with annex 16, whereas the nvPM probe line was diluted with particle free N_2 gas via a Dekati DI-1000 ejector diluter and conveyed to the measurement suite using a 25 m long, 7.9 mm i.d., carbon-loaded, electrically grounded polytetrafluoroethylene (PTFE) tube maintained at 60^0C in accordance with SAE AIR 6241.

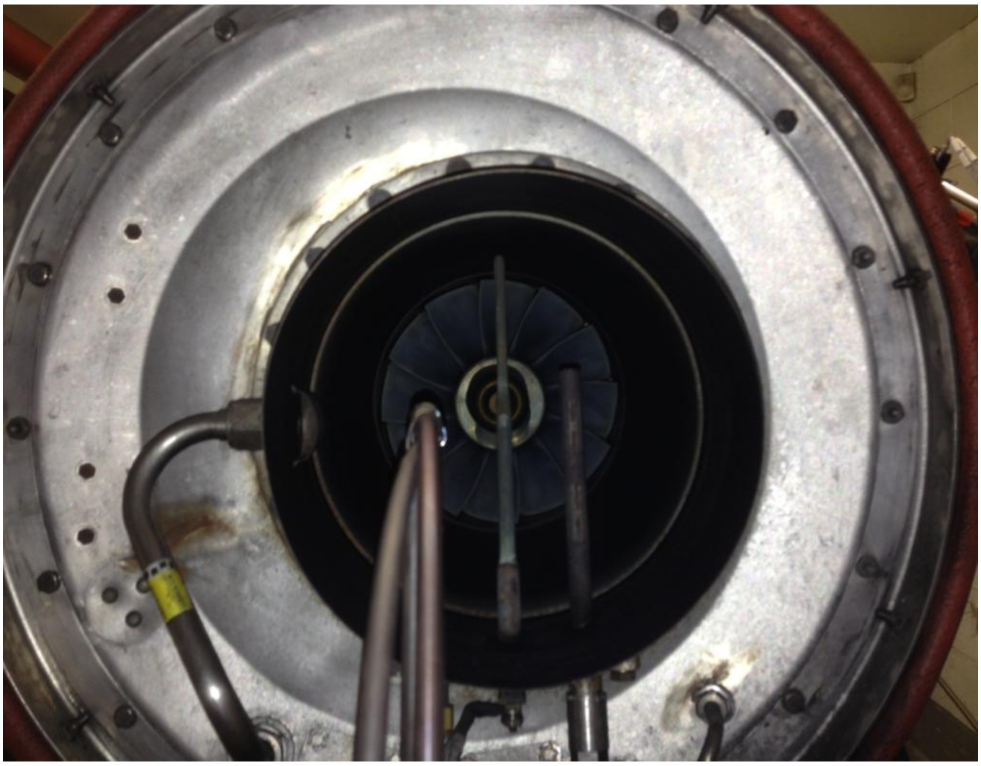

Figure 2. Photograph of the exit plane for the Garrett Honeywell GTCP85 APU gas turbine engine. Two sampling probes (upper PM probe, lower gas probe) are almost collocated and positioned to the left of centre. Other probes structures in the centre and right of centre are engine management sensors.

Operating procedure

The standard procedure for the operation for the APU is to commence engine start using Jet A-1 fuel, attain a stabilized engine condition for at least 2 minutes, then switch to the fuel blend under test via a three way valve such that continuous operation is maintained. The time lag for the test fuel to enter the engine is approximately 15 seconds. The measurement procedure commences following an observed stabilized engine condition for a further 2 minutes. This procedure is common to all engine tests.

The time of operation at each of the three engine conditions is approximately 6 minutes, running two cycles from high power stepping down to idle in three steps. This sequence follows the three standard APU set point conditions of high load for main engine start (with full bleed); environmental conditioning system load (when APU is driving air conditioning and power) and idle load (with no bleed or power demand). The sequence steps downward in power in order to minimize any engine warm up effects, which is an important consideration as subtle differences in emissions are observed at different engine temperatures (for a nominally ‘cold’ engine, the fuel does not entirely vaporise and higher emissions of hydrocarbons, nitrogen oxides and carbon monoxide, are produced which then diminishes as the engine reaches operating temperature). The sequence is cycled twice to validate the repeatability of the measurements. Hence the minimum engine time to complete an engine test on a particular fuel will be approximately 36 minutes, this is shown schematically in Figure 3.

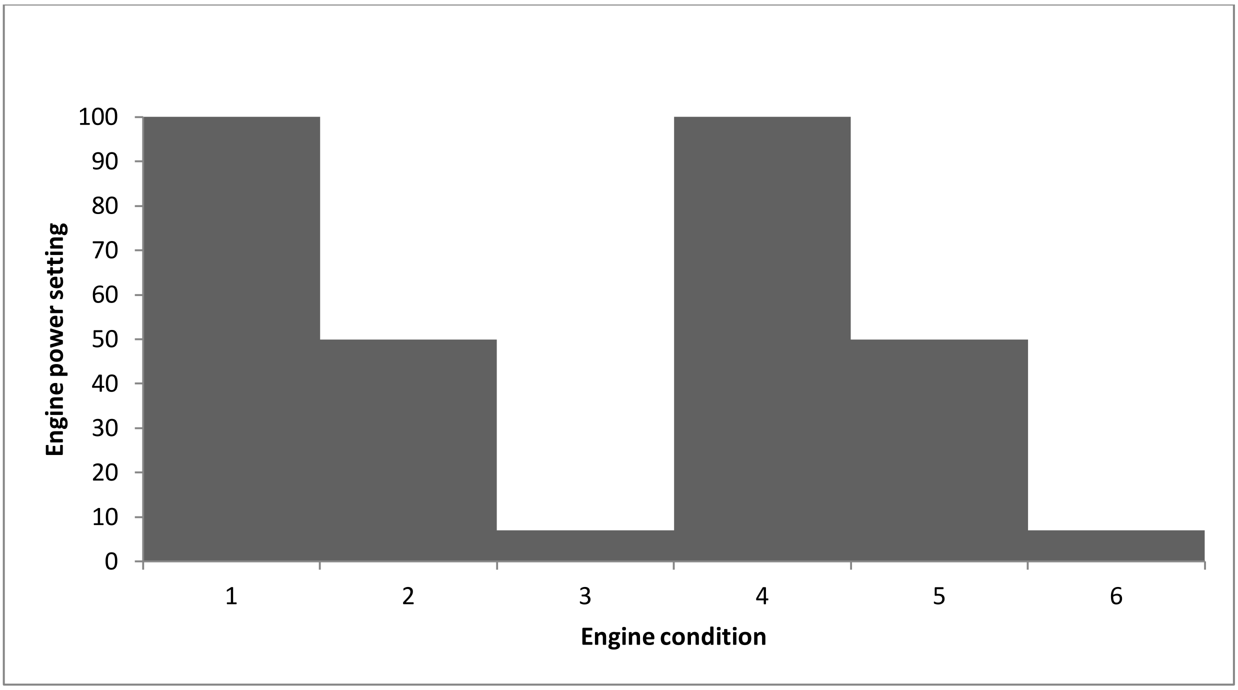

Figure 3. Schematic illustration showing the sequence of the engine conditions used for each of the fuel blends under test.

3 Additional subtasks

Two additional subtasks have been added to the original scope of this task as outlined in the ITAKA description of work.

Additional subtask 1: Emissions from non-certified upper blend ratios

The ASTM certification for HEFA biofuels currently specifies an upper blend ratio of 50% by volume as a cautionary upper limit to address a variety of concerns raised by ASTM committee members. Commercial airlines cannot legally operator revenued flights above this upper blend limit and are in general unwilling to breach this limit even for unrevenued flights as a re-certification of equipment will be required. At the commencement of the ITAKA project, the APU test facility was also subject to these same limitations as the engine was owned by British airways. Hence the original scope of this task was limited to blend ratios in the 0% to 50% range as specified in the DoW. However, efforts to purchase this engine have been on-going and ownership has now passed to the Low Carbon Combustion Centre. In consequence it has been possible to extend the scope of the task to embrace an assessment of atmospheric emissions from non-certified upper blend ratios in the range 50% to 100% biofuel beyond those currently certified. Whilst emissions data in this blend range is not of current commercial interest, it is however of significant scientific interest as there are very few datasets that attempt to characterise emissions from these upper fuel blend ratios within the wider literature, and furthermore, there are no datasets that extensively cover the full range of blend ratios.

Data from this additional subtask have been incorporated into the body of the main results section.

Additional subtask 2: Non-volatile particulate matter characterization with SAE compliant reference system

The research conducted in this third party collaborative project brings significant gearing to ITAKA activities and supporting research in terms of interaction with leading international specialists on aviation nvPM emissions and participation in cutting-edge developments. Methods and data developed in this subtask cut across three significant axes of innovation: 1) SAE ARP probe development and validation; 2) the development of data for the CAEP alternative fuels emissions database; 3) the detailed characterization of nvPM emissions from ITAKA biofuel, that crucially can be referenced to a well defined and standardized measurement system.

As one of the founder members of the EASA funded SAMPLE consortia that worked on improving measurement procedures for aircraft nvPM emissions and the development of data for E-31 committee, MMU initiated this additional subtask with the agreement of SENASA. No reference to this additional subtask is contained within the ITAKA DoW.

The nvPM characterisation using the SAE reference probe represents an additional value added but zero cost extension to the EU funded ITAKA project. In this additional subtask (a transatlantic collaboration involving FAA funding), researchers from the Missouri University of Science & Technology (MST) have worked together with the ITAKA measurement team contributing both their considerable expertise and data from their state-of-the-art PM emissions diagnostic suite. This diagnostic suite (one of only three worldwide) is compliant with the 2013 specification in SAE AIR

6241 for nvPM emissions measurements, a specification that will form the basis of the ICAO ARP for nvPM emissions measurement due to be introduced in 2016. For the completion of this work, five researchers from MST and the complete nvPM diagnostic suite was shipped to the UK, and all measurements were made concurrently at the APU test facility.

Measurements with this state-of-the-art reference probe are significant and establish three salient points of innovation:

1) SAE ARP development and validation: CAEP expects the delivery of a non-volatile PM standard to supersede the current smoke number measurement by the end of 2016. To develop this, EASA and the other Regulatory agencies (FOCA, CAA, FAA, EPA) have requested the SAE E-31 committee to provide a ballot-ready non-volatile PM mass and number Aerospace Recommended Practice (ARP). Whilst the development of this standard is theoretically on-going, a significant step came with the publication of SAE AIR 6241 which defines a procedure for the continuous sampling and measurement of nvPM emissions from aircraft turbine engines and on which the final ARP will be based.

The AIR 6241 compliant North American Reference System operated by Missouri S&T (MST) has been operated at a number of testing venues including SR Technics in Zurich, as well as several OEM facilities in Canada and the US. However, to date all of the testing and inter-comparisons of the nvPM reference systems have been conducted using conventional Jet A-1 fuel, and this is the first time that any AIR 6241 compliant system has been evaluated using biofuel or biofuel blends. The absence of direct experience with biofuels is significant, since a number of previous studies have demonstrated a dramatic reduction in PM emissions with decreasing fuel aromatic content, which is a key characteristic of HEFA fuels. Acknowledged or possible changes in the nature of the emitted nvPM include perturbed size / number / mass distribution, with smaller geometric mean diameter and increased PM density in relation to Jet A-1. Measurements made with the MST nvPM system on ITAKA biofuel represented a significant opportunity to evaluate these knowledge gaps and to assess the robustness of the measurement system for gas turbine engines burning biofuels and their blends. It is an important milestone for the development of the ARP.

2) Data for the nvPM emissions database: The Particulate Matter Task Group of CAEP WG3 has constituted an ad-hoc group called “MEASURE” that will develop a measurement plan with schedules for testing and developing a non-volatile PM emissions database. Central to this database, the AIR 6241 compliant reference systems represent the ‘gold standard’ as they are standardized and robustly characterized nvPM measurement systems. However, the round-robin OEM testing being conducted by each of the nvPM reference systems is undertaken using regionally sourced Jet A-1 fuel which is unsurprisingly widely variable in its chemical and physical properties. Consequently, the database will be subject to an undefined level of uncertainty that requires some understanding of the relation between fuel properties and nvPM emission characteristics to quantify. This is the first time that any AIR 6241 compliant system has been evaluated using biofuel or biofuel blends, and it is intended that data from the ITAKA biofuel emission test program feed into this ICAO adhoc group via a subject matter expert. The information gained may be used to estimate bounds of uncertainty, and develop possible future fleet emission scenarios for PM as sustainable aviation biofuels become integrated into the supply infrastructure. Understanding how this potential change in the composition of the fuel supply might affect emissions is important, and of particular significance is the appreciable reduction in the emission of nvPM that is strong characteristic of HEFA biofuel blends.

3) The detailed and robust characterization of nvPM emissions from ITAKA biofuel: Detailed high fidelity data on how the emissions characteristics change with different biofuel blend fractions are currently relatively sparse within the literature. Furthermore any inter-comparison between the different datasets in the literature is perplexed by variations in fuel properties (which are often poorly reported), appreciable differences in engine test hardware, and in the case of PM measurements, the use of dissimilar non-standardised sample lines and procedures (Note. It was precisely because of these differences between measurement systems that led to the substantial body of research that underlies the development of AIR 6241 outlined above).

Consequently, it is significant that the nvPM characterization data reported here for the ITAKA MCA batch biofuel were measured on an AIR 6241 compliant system: the data are distinct in that they were obtained on well characterized state-of-the-art instrumentation, but also and perhaps crucially, they are extremely robust in that they can be referenced to a defined and standardized measurement system.

4 Results: Engine performance data (MCA batch fuel)

A change in the properties of the fuel powering a gas turbine engine can have a significant influence on the engine cycle and performance. In the following section we examine the effect of different MCA biofuel blend ratios has on fuel flow, shaft speed and exhaust gas temperature.

Fuel flow

The chemistry and properties of the ITAKA MCA batch biofuel are appreciably different from those of the baseline Jet A-1. In relation to fuel flow the most significant of which is the specific energy density.

Figure 4 shows the change in the engine fuel flow as a function of the biofuel blend ratio. For the three engine conditions there is a progressive decrease in the mass fuel flow with an increasing proportion of biofuel in the blend. The specific energy of density of the MCA biofuel and baseline Jet A-1 are given in Table 2. To a first order approximation, the rate of decrease in the mass fuel flow to the engine scales in proportion to the specific energy of the fuel adjusted for blend ratio, such that the rate of energy input to the engine remains constant for a given engine condition. This trend of reduced fuel flow with increasing fuel specific energy density is consistent with data previously reported in the literature, and flight performance data reported by Airbus in ITAKA deliverable D4.1.

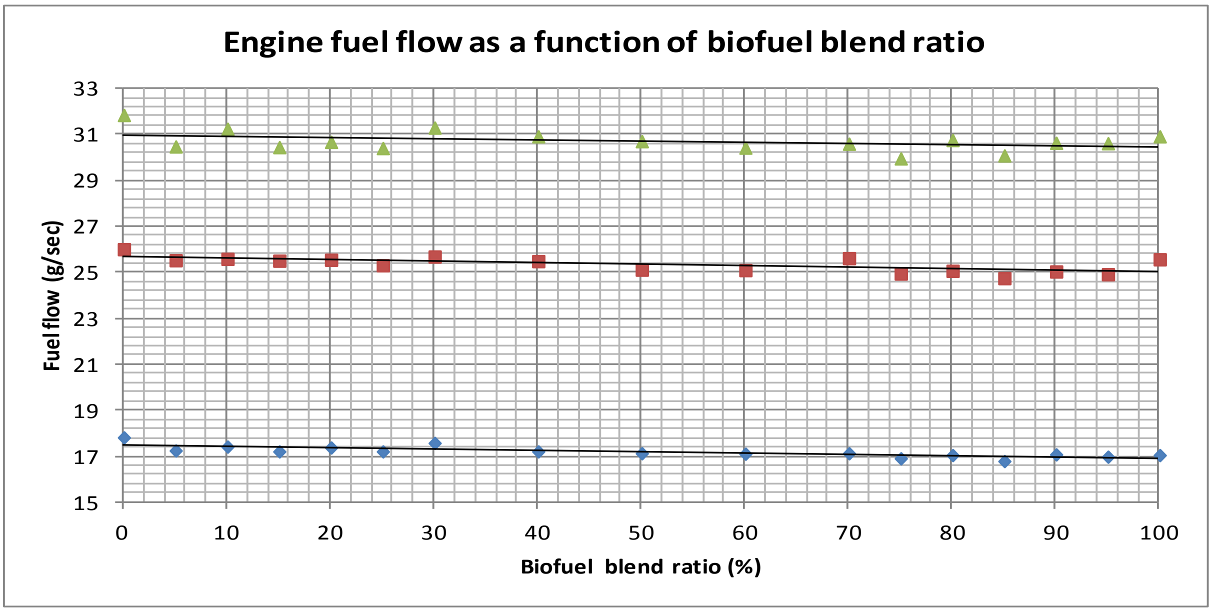

Figure 4. Engine fuel flow as a function of biofuel blend ratio. Key: Blue NL (no load); Red ECS (environmental control system); Green MES (main engine start). Uncertainty on an individual fuel flow measurement point is estimated to be +/- 0.2 g s^{-1}. Least squares linear trend lines are indicated for reference.

Note that fuel flow is measured in mass per unit time, as is the convention in aviation. If the fuel flow where to be measured in volume per unit time there would be a corresponding increase in flow as the MCA batch biofuel has a lower density (see Table 2).

Shaft speed

For the Garret APU, the engine management system utilises temperature, pressure, and shaft speed data to maintain optimum efficiency of operation. Conventionally, the APU functions at a constant shaft speed. Whilst similar control systems may be found on aviation turboprops and turboshaft engines, it is not found on turbofan engines where the shaft speeds is varied and determines the appointed thrust. It is nevertheless a key performance indicator and its dependence on biofuel blend ratio merits investigation.

Figure 5 shows the change in the engine shaft speed measured in revolutions per minute (RPM) as a function of the biofuel blend ratio. For the three engine conditions there is a progressive decrease in the RPM with an increasing proportion of biofuel in the blend. The decrease in shaft speed from 100% Jet A-1 to 100% MCA biofuel is approximately 300 RPM for each of the engine conditions. In each case the decrease is a statistically significant with linear correlation coefficients, R^2 of 0.91, 0.89, and 0.61 respectively. The higher variability in the data for the MES engine condition being indicative of operator control and is to be expected.

However an explanation for this clear dependency upon biofuel blend ratio is not fully understood and is currently subject to further analysis which will be reported as an addendum.

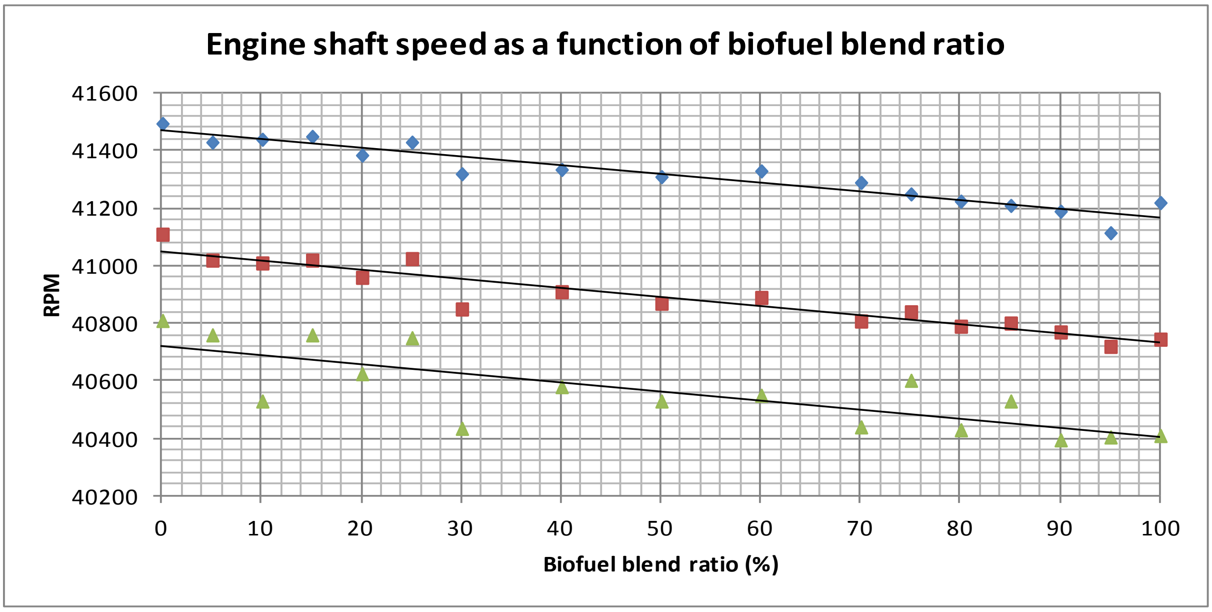

Figure 5. Engine shaft speed measured in RPM as a function of biofuel blend ratio. Key: Blue NL (no load); Red ECS (environmental control system); Green MES (main engine start). Uncertainty on an individual shaft speed measurement point is estimated to be +/- 50 rpm. Least squares linear trend lines are indicated for reference.

Exhaust gas temperature

The exhaust gas temperature is an important parameter that is routinely used as an indicator of the overall 'health status' of an engine. It is therefore important to characterise what effect blend ratio might have upon this parameter.

Figure 6 shows the change in the engine exhaust gas temperature (EGT) as a function of the biofuel blend ratio. For the MES engine condition where the operator uses EGT as the reference metric to set the engine condition there is no drop in EGT with biofuel blend ratio as expected. However, for the NL and ECS engine conditions there is a subtle but statistically significant decrease in the EGT with increasing proportion of biofuel in the blend. This decrease is approximately 8°C from 100% Jet A-1 to 100% biofuel and is noteworthy as 1) the NL and ECS engine conditions the engine management system has total control over the condition and is highly reproducible; and 2) this effect has not be reported previously in the literature.

From a theoretical standpoint, there are a number of possible explanations why the EGT should edge to marginally lower temperatures as the fraction of MCA biofuel increases, however, the increase in the fuel H/C ratio and the concurrent drop in shaft speed are confounding factor that may also be connected, and so further analysis is necessary which will be reported as an addendum.

A qualitative comparison of the EGT data with the Airbus report 'Engine performance analysis of T7.2.2B MCA batch on Airbus flights' (ITAKA deliverable D4.1) shows that the two datasets are not inconsistent. However it has not been possible to follow up with a quantitative assessment as access to the raw flight test data through either KLM or Airbus has not been forthcoming, and deliverable D4.1 goes no further than indicating that the EGTs are within bounds. Consequently the pursuit of corroborating data is currently being sort through research partners outside of the ITAKA consortium.

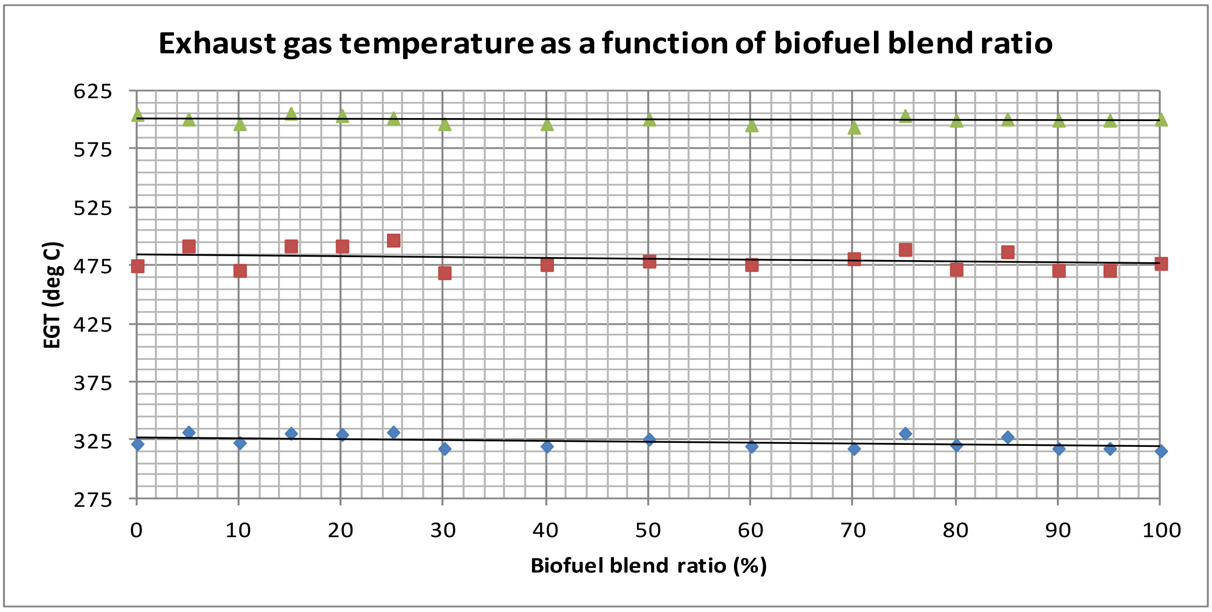

Figure 6. Engine exhaust gas temperature as a function of biofuel blend ratio. Key: Blue NL (no load); Red ECS (environmental control system); Green MES (main engine start). Uncertainty on an

individual EGT measurement point is estimated to be +/- 10 ^{o}C. Least squares linear trend lines are indicated for reference.

5 Results: Engine emissions data (MCA batch fuel)

In the following sections exhaust emissions data are given for the individual ICAO species (SN, UHC, CO, and NOx) at the three standard APU engine test conditions. Where appropriate, data have been corrected to ISA conditions using SAE ARP 1533 / AIR 6241 standardised methods.

Ambient atmospheric data

Ambient temperature, ambient pressure, and relative humidity were recorded throughout the experimental campaign, and the ranges of values for these parameters were: 14.0 – 20.6 ºC, 1024.7 – 1031.1 mb, and 61 – 85%, respectively. The ambient conditions of temperature, pressure and relative humidity are shown in Figure 7 plotted against measurement point so that a direct comparison with emissions data can be made: For some emission species there is a dependency on ambient conditions which 1) perturb measurement conditions away from ISA, although this is correctable, and 2) can perturb the combustion process itself which are more difficult to correct.

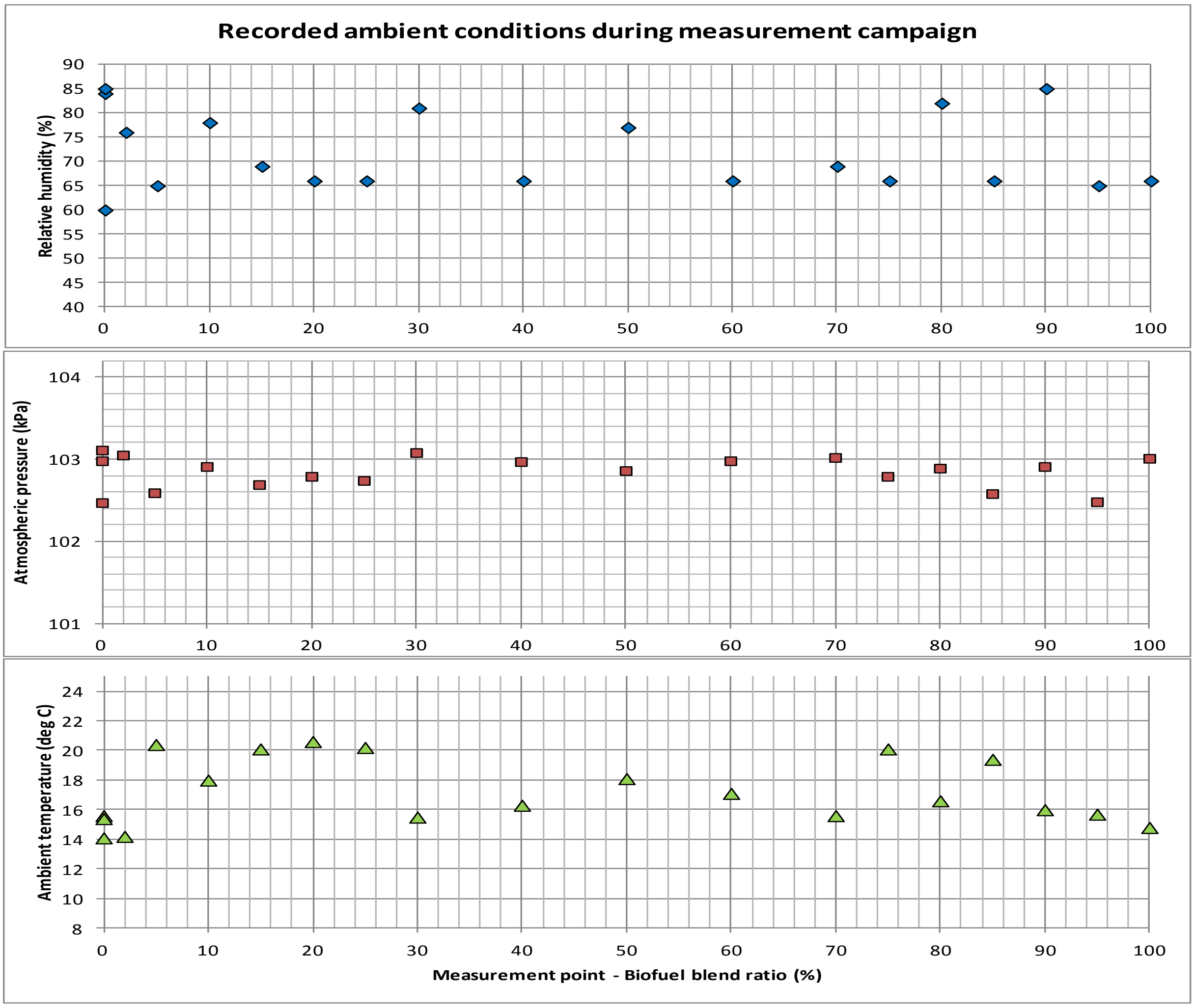

Figure 7. Record of ambient conditions at each measurement point. Upper: relative humidity (%), middle: atmospheric pressure (kPa), lower: ambient temperature (deg C)

Smoke number data

Whilst the Garrett Honeywell GTCP85 APU gas turbine engine is representative of comparatively recent APU technology, the overall emissions remain relatively high in comparison to many modern aero engines. This difference is nevertheless advantageous when measuring metrics such as smoke number: Modern aero engines may have a SN in the 0 – 5 range with an uncertainty of +/-3 with the consequence that the measurements of SN for low aromatic biofuels rapidly become indefinable as the blend ratio increases. This is not the case for the Garret APU where the SN is typically in the 30 – 40 range with a similar uncertainty of +/-3 on an individual SN measurement point.

Figure 8 shows the normalised SAE engine smoke number of the exhaust emissions as a function of the biofuel blend ratio for the three different engine conditions. Each data point represents the average of at least four smoke number measurements.

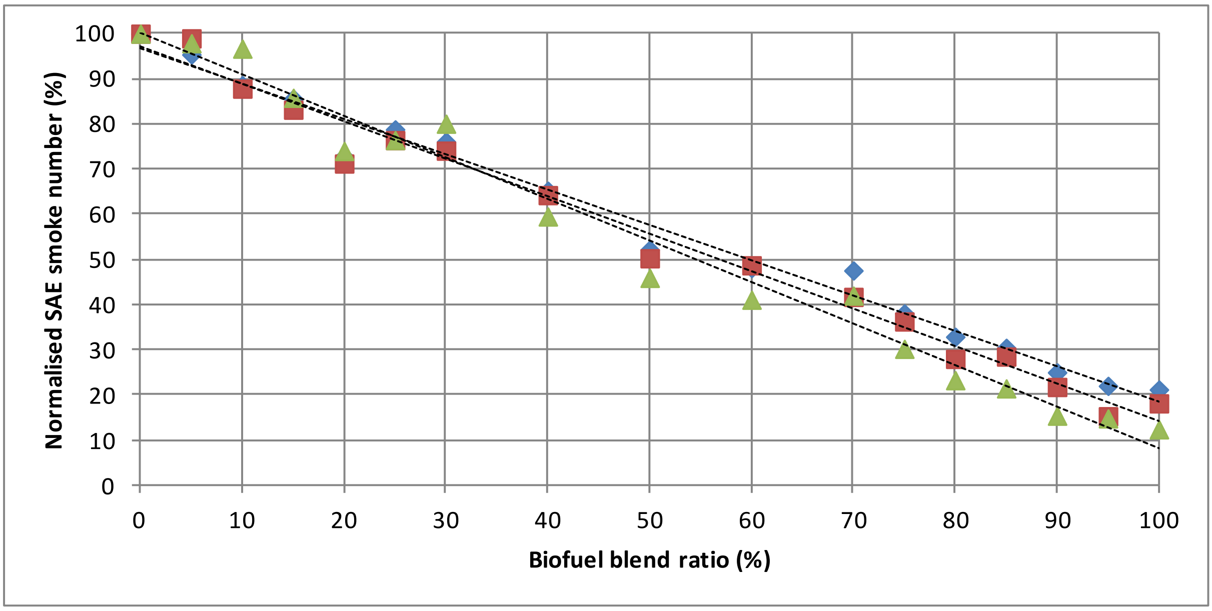

Figure 8. Normalised SAE smoke number of the exhaust emissions from the Garrett Honeywell GTCP85 APU gas turbine engine as a function of biofuel blend ratio and for three different engine conditions. Key: Blue NL (no load); Red ECS (environmental control system); Green MES (main engine start). Uncertainty on SN measurement points is estimated to be +/- 10%. Least squares linear trend lines are also indicated for reference.

The data in Figure 8 show a pronounced reduction in SAE smoke number as a function of increasing MCA biofuel blend ratio. These data are consistent with data reported in the literature for HEFA derived biofuels [eg. Rye et al, 2012]. The distinction between the data reported here and those found elsewhere in the literature is the large number of data points that clearly demonstrate that the relation between SAE smoke number and blend ratio is linear to a good first approximation. Furthermore this linear relation exists for each engine condition, and the linear correlation coefficients fit for each engine condition R^2 >0.98 (indicated by the broken line). The SN reduction for this hardware and at all three engine conditions is between 0.8% - 0.9% for each percent increase in MCA biofuel in the blend fraction.

For this gas turbine engine operating on Jet A-1, the SN ranking for different engine conditions is nominally NL ≥ ECS > MES, although differences are small. Within the figure, the cross over in SN for different engine conditions at low to mid blend ratios and the apparent divergence at higher blend ratios are interesting features; however the uncertainty in SN data prevents any meaningful interpretation. Detailed characterisation of the nvPM emissions (discussed below) indicate that these features probably result from a change in the capture efficiency of the Whatman #4 SN paper which occurs in response to a shift in the number, mass and size distributions.

Characteristics of nvPM

The sampling and measurement system employed for nvPM characterisation was compliant with the specifications defined in the Society of Automotive Engineers Aerospace Information Report 6241 [SAE, 2013]. A complete description and performance evaluation of the AIR 6241 compliant North American mobile Reference System operated by the Missouri University of Science and Technology to measure nvPM emissions can be found in Lobo et al 2015.

In this study, the probe used to extract nvPM emissions samples was connected to a 3-way splitter using a 7.5m long, 7.9mm i.d. thin walled stainless steel tubing maintained 160^{0}C. The nvPM sample was diluted by particle free dry nitrogen via a Dekati DI-1000 ejector diluter and conveyed to the measurement suite using a 25 m long, 7.9 mm i.d., carbon-loaded, electrically grounded polytetrafluoroethylene (PTFE) tube maintained at 60^{0}C.

The nvPM number-based emissions were measured using an AVL Particle Counter Advanced (APC) while nvPM mass-based emissions measurements were performed using an Artium Laser Induced Incandescence LII-300 (LII) and an AVL Micro Soot Sensor (MSS). Non-volatile particle size distributions, which are not specified in AIR 6241 were measured using the Cambustion DMS500. The CO_2 concentration in the diluted nvPM line was measured using a LiCor 840A NDIR detector.

Number and mass of nvPM emissions

For each fuel blend, the nvPM number-based emission indices (EIn) and mass-based emission indices (EIm) were compared against those for the baseline Jet A-1. A summary of observations is as following:

- For a given fuel blend, the highest nvPM emissions were observed for the NL engine condition, followed by ECS, and then MES as would be expected.
- For different fuel blends, an almost linear reduction in nvPM number (EIn) was observed with an increasing proportion of MCA biofuel. This was the case for each of the engine conditions.
- For different fuel blends, an almost linear reduction in nvPM mass (EIm) was observed with an increasing proportion of MCA biofuel. Although the data show evidence that the mass based emissions index asymptote towards a fixed and maximum reduction at the higher fuel blend ratios in excess of 80%. This was the case for each of the engine conditions.

- For all fuel blends, the magnitude of the nvPM EIn and EIm reductions were highest at the MES engine condition, followed by ECS, and then the NL engine condition.
- For 100% MCA biofuel, the percent reductions in EIn were 74% (MES) > 66% (ECS) > 61% (NL), whereas the corresponding percent reductions for EIm were 93% (MES) > 91% (ECS) > 88% (NL).
- For 50% MCA biofuel, the percent reductions in EIn were 38% (MES) > 32% (ECS) > 29% (NL), whereas the corresponding percent reductions for EIm were 52% (MES) > 50% (ECS) > 49% (NL).

The magnitude of reductions in nvPM EIn and EIm are comparable to those reported in the literature for other gas turbine engines burning paraffinic fuels [Lobo et al, 2011; Timko et al, 2010; Corporan et al 2011, amongst others], and this trend has also been observed for larger gas turbine engines at high thrust conditions [Lobo et al, 2011; Beyersdorf et al, 2014] and a turboshaft engine [Cain et al, 2013] burning paraffinic and surrogate fuels.

The average EIm reduction ratios taken over all three engine operating conditions for the 100% MCA and 50% MCA fuel blends were 0.09 ± 0.02 and 0.40 ± 0.02, respectively. These values compare well with those reported for a CFM56-2C1 turbofan engine burning a pure FT fuel (0.14 ± 0.05) and a 50:50 blend of FT and JP-8 fuels (0.34 ± 0.15) [Beyersdorf et al, 2014].

Data for the reduction in the number and mass based nvPM emission index normalised with respect to the baseline Jet A-1 fuel are shown in Figure 9 and Figure 10 for the ECS engine operating condition. Data for all three engine conditions display typically similar trends though are quantitative dissimilar. Figure 9 shows the nvPM number-based emission index may be reduced by more than 30% for a 50:50 fuel blend, rising to more than 65% for neat MCA biofuel. The corresponding reduction in the nvPM mass-based emission index shown in Figure 10 are more than 50% for a 50:50 fuel blend, rising to more than 90% for neat MCA biofuel.

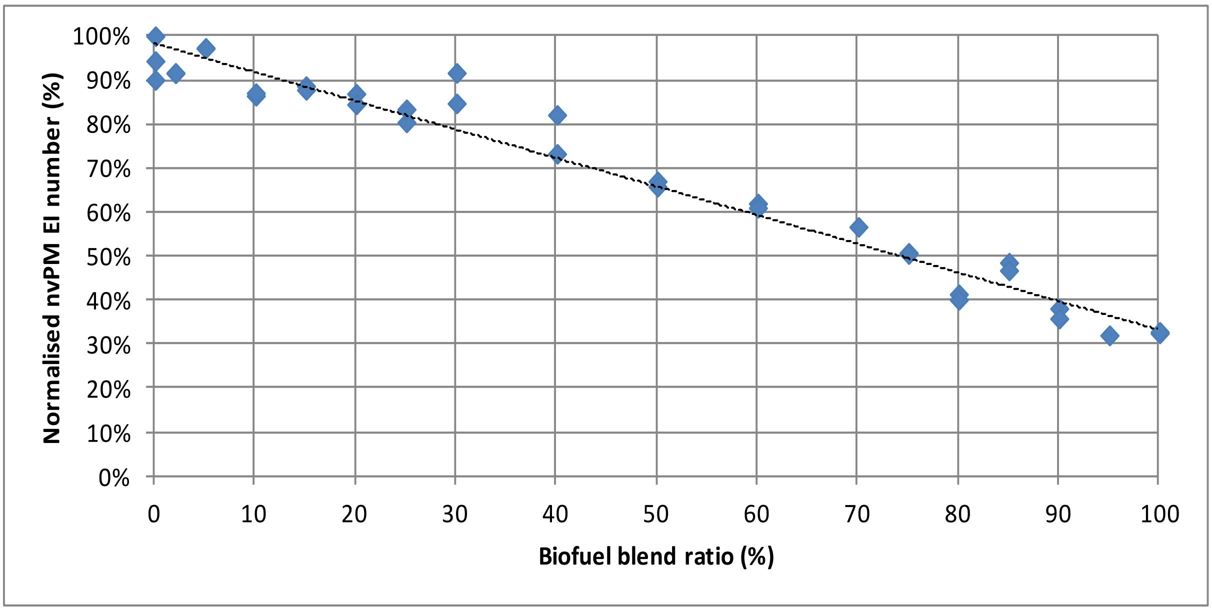

Figure 9. The nvPM number-based emission index normalised with respect to the Jet A-1 baseline fuel and shown as a function of biofuel blend ratio at the ECS engine operating condition. The least squares linear trend lines is indicated for reference.

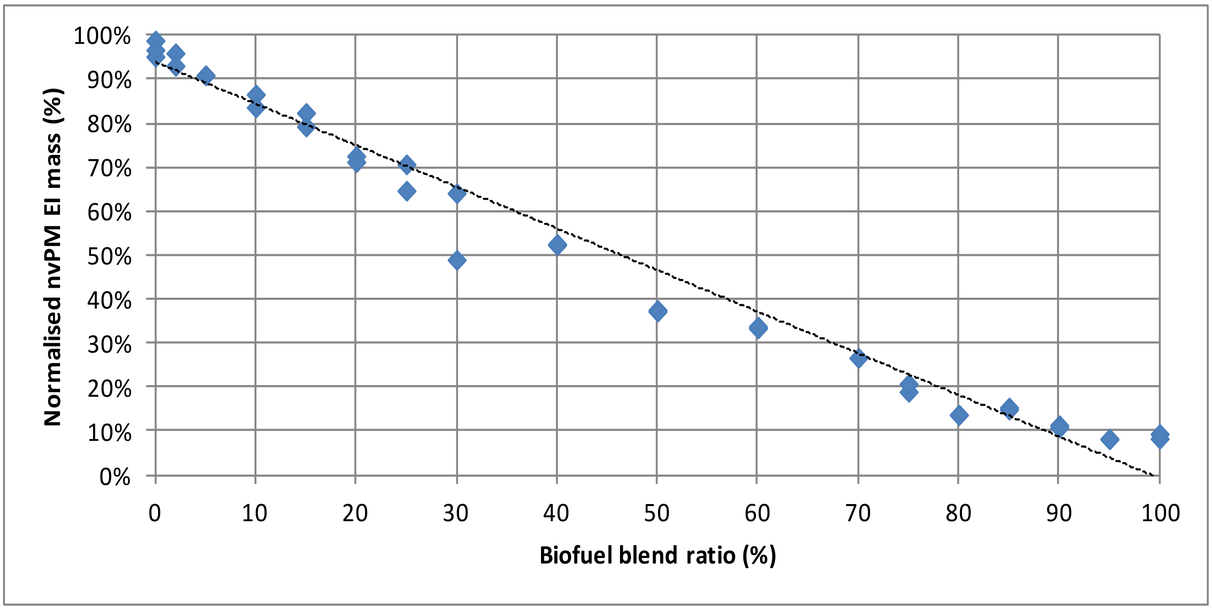

Figure 10. The nvPM mass-based emission index normalised with respect to the Jet A-1 baseline fuel and shown as a function of biofuel blend ratio at the ECS engine operating condition. The least squares linear trend lines is indicated for reference.

Size distribution of nvPM emissions

For all fuel blends and all three engine conditions, the nvPM emissions exhibited a lognormal size distribution. This lognormal size distribution then narrows and there is a shift to smaller sizes in the geometric mean diameter as the proportion of MCA biofuel in the fuel blend increased. This effect is typified in Figure 11 which shows the nvPM EIn size distribution for selected fuels at the NL engine operating condition [Lobo et al 2015b]. For this case, the mean diameter in the ultrafine particulate emissions from shifts from ~ 50 nm down to ~ 22 nm.

The significant reduction in the nvPM mass with blend ratio discussed earlier is clearly manifest within this shift in the size distribution. These results are consistent with those reported for other gas turbine engines burning conventional and alternative fuels [Lobo et al, 2011; Cain et al, 2013; Lobo et al, 2015; amongst others].

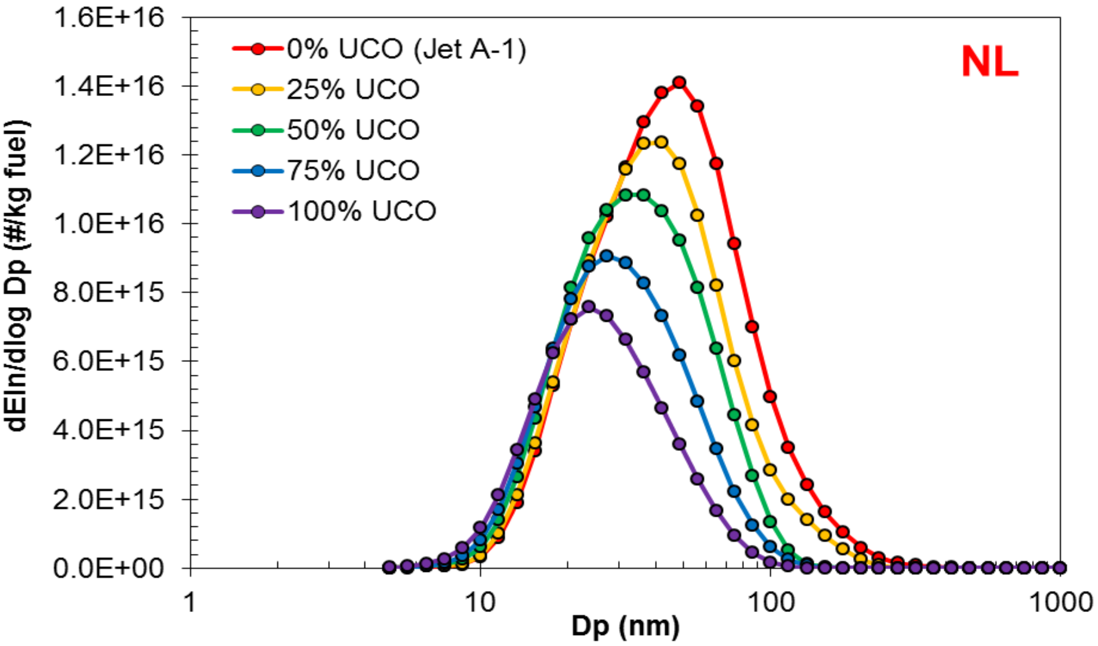

Figure 11. The nvPM emission EIn size distributions for selected biofuel blends at the NL engine condition. Mean particulate diameter shifts from ~50 nm for Jet A-1 to ~22 nm for 100% MCA biofuel.

The epidemiology for airborne particulate matter strongly suggests that there is no safe limit for human exposure [for example see Barrett et al, 2010]. However, there is considerable uncertainty as to the physiological mechanisms involved, and accepted thinking currently point towards PM surface area being a key parameter. Hence a large number of small particles are generally considered to have a greater epidemiological effect than an equal mass of larger particles that are fewer in number.

On this basis, a very rough estimate on the local air quality impact of the MCA batch biofuel may be derived: The total surface area of the emitted PM can be estimated from the product of the number of particles with the square of their mean diameter. Hence for the case of the 50% MCA fuel blend ratio, where the shift in mean particulate size is from ~50nm down to ~30nm, and the number of emitted particles drops by ~30%, then the total surface area of the emitted PM drops by 75% which is a significant fraction. Hence the overall effect of the reduction in both size and number of airborne PM is net positive and is likely to improve local air quality.

Unburned hydrocarbons emissions

Figure 12 shows the normalised concentration of unburned hydrocarbons (UHC) in the exhaust emissions as a function of the biofuel blend ratio for the three different engine conditions. Each data point is normalised with respect to the NL Jet A-1 emissions of UHC and represents the average of the two measurement cycles. The emissions ranking order NL > ECS > MES from highest to lowest is as might be expected for a gas turbine, with highest emissions at low powers.

Scatter in the data points is normal and is ordinarily reflective of the measurement error that exists when measuring very low concentrations of UHC, however in this case a comparison of data points between different engine conditions and at a fixed blend ratio suggests the presence of an error that is common. A comparison of UHC emissions with ambient condition data shows a slight correlation with ambient temperature (R^2 ~0.25), pressure (R^2 ~0.23), and relative humidity (R^2 ~0.28). This dependence on ambient conditions adds to the measurement uncertainty and is difficult to correct since the relation is not fully characterised.

The least squares trend line through the data infers a slight linear decrease in the emission of UHC with an increasing fraction of MCA biofuel in the blend, however the correlation coefficients lack conviction (for NL R^2 = 0.20; for ECS R^2 = 0.09; for MES R^2 = 0.05; all with n=18) and are clearly biased by just a few outlying data points. Hence, such a claim is difficult to justify and a null change seems more justifiable. Emission indices for UHC on this hardware show a similar null change.

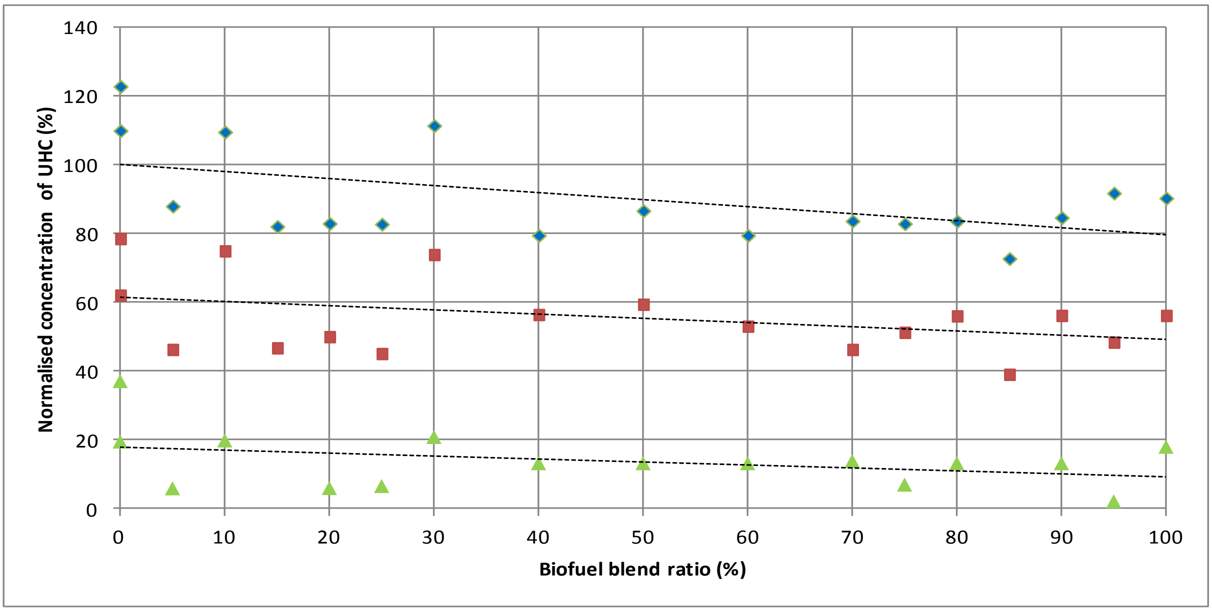

Figure 12. Normalised concentration of unburned hydrocarbons in the exhaust of the Garrett Honeywell GTCP85 APU gas turbine engine as a function of biofuel blend ratio and for three different engine conditions. Data is normalized with respect to UHC emissions for Jet A-1 under no load. Key: Blue NL (no load); Red ECS (environmental control system); Green MES (main engine start). Uncertainty on individual UHC measurement points is estimated to be +/- 2 ppm. Least squares linear trend lines are indicated for reference.

Carbon monoxide emissions

Figure 13 shows the normalised concentration of carbon monoxide (CO) in the exhaust emissions as a function of the biofuel blend ratio for the three different engine conditions. Each data point is normalised with respect to the NL Jet A-1 emissions of CO and represents the average of the two measurement cycles. Interestingly the emissions ranking order for CO on this hardware is ECS > MES > NL from highest to lowest.

Again a comparison of data points for different engine conditions and at a fixed fuel blend ratio implies the presence of an error that is common. A comparison of CO emissions with ambient condition data shows a slight correlation with ambient temperature (R^2 ~0.24), pressure (R^2 ~0.35), these being strongest for the NL condition, but little relation with relative humidity (R^2 ~0.09). This dependence on ambient conditions adds to the measurement uncertainty and scatter.

The least squares trend line through the data infers a small linear decrease in the emission of CO with an increasing fraction of MCA biofuel in the blend. In this case correlation coefficients do infer the existence of a relation (for ECS R^2 = 0.71; for NL R^2 = 0.64; for MES R^2 = 0.51; all with n=17). For each of the three engine conditions, the slope of the trend line suggests the decrease in the emission of CO is approximately -0.5 ppm for each percent increase in blend ratio, which equate to around 50ppm over the range 100% Jet A-1 to 100% MCA biofuel. Emission indices for CO on this hardware show a similar decreasing trend.

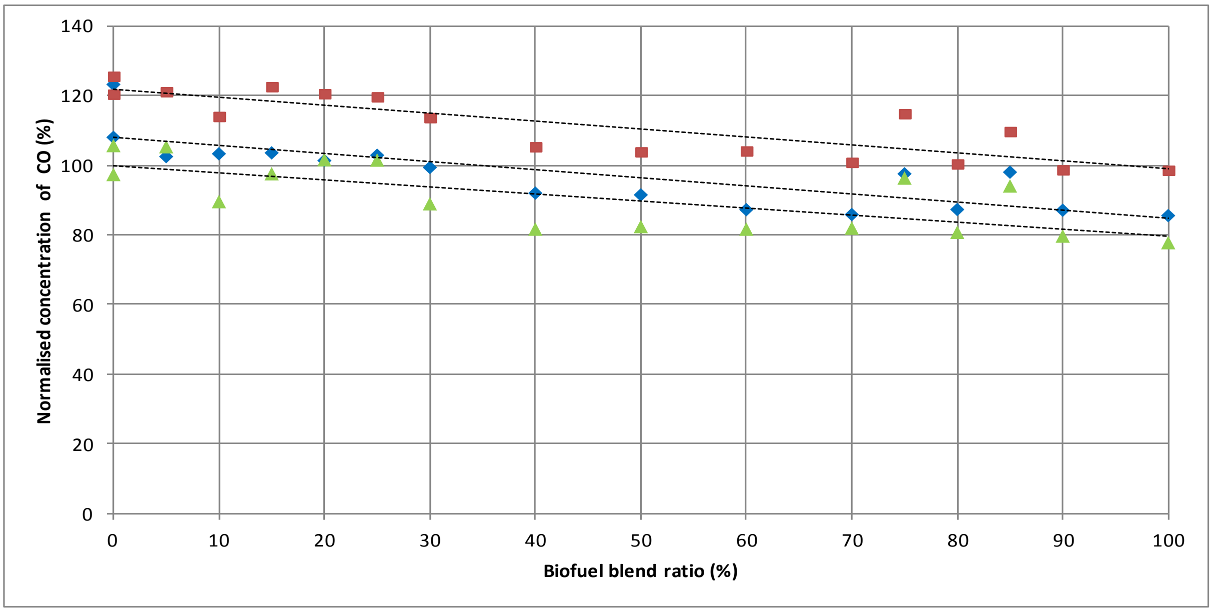

Figure 13. Normalised concentration of carbon monoxide in the exhaust of the Garrett Honeywell GTCP85 APU gas turbine engine as a function of biofuel blend ratio and for three different engine conditions. Data is normalized with respect to CO emissions for Jet A-1 under no load. Key: Blue NL (no load); Red ECS (environmental control system); Green MES (main engine start). Uncertainty on individual CO measurement points is estimated to be +/- 10ppm. Least squares linear trend lines are indicated for reference.

Oxides of nitrogen emissions

Figure 15 shows the normalised concentration of oxides of nitrogen (NOx) in the exhaust emissions as a function of the biofuel blend ratio for the three different engine conditions. Each data point is normalised with respect to the NL Jet A-1 emissions of NOx and represents the average of the two measurement cycles. The emissions ranking order MES > ECS > NL from highest to lowest tracks the engine temperature and EGT as might be expected.

As previously, a comparison of data points for different engine conditions and at a fixed blend ratio implies the presence of an error that is common, since all three data points tracking together. However, in this case a comparison of NOx emissions with ambient condition data does not reveal any noteworthy correlation with ambient temperature (R^2 ~0.04) or atmospheric pressure (R^2

~0.07), although a weak correlation with relative humidity (R^2 ~0.16) may exist. This dependence on ambient conditions adds to the measurement uncertainty and scatter, although instrument measurement errors are also present.

The least squares trend line through the data infers a small linear decrease in the emission of NOx with an increasing fraction of MCA biofuel in the blend, however the correlation coefficients lack authority (for MES R^2 = 0.22; for ECS R^2 = 0.26; for NL R^2 = 0.29; all with n=18) and are clearly biased by just a few outlying data points. Hence, it is difficult to state with any reasonable confidence that such a relation exists and a null change seems more justifiable. Emission indices for NOx on this hardware show a similar null change.

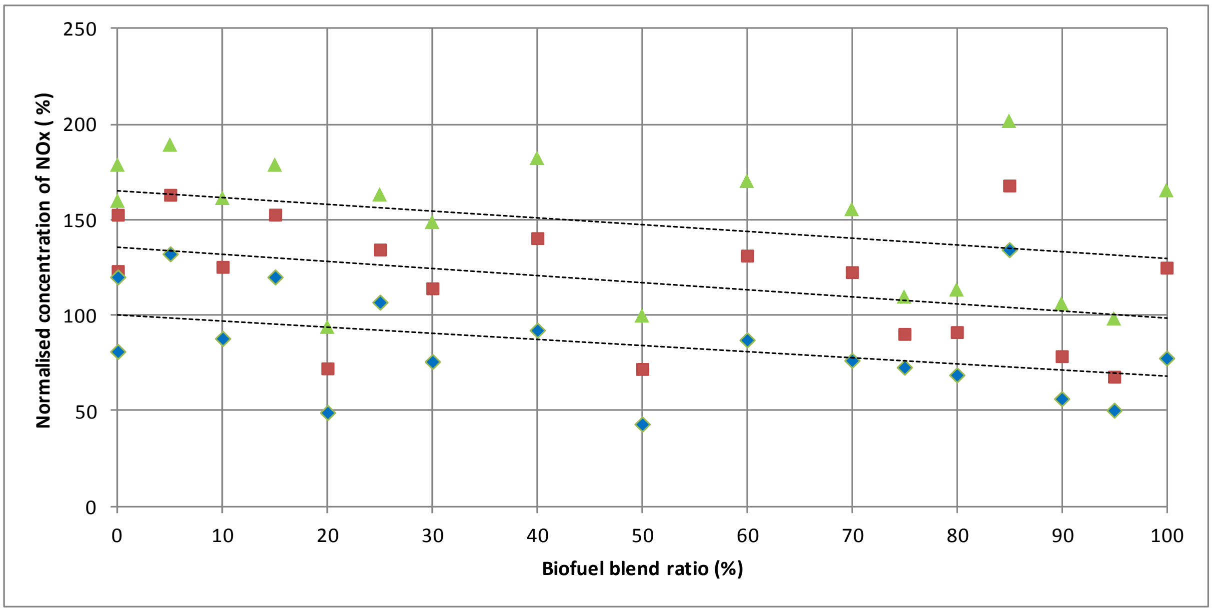

Figure 14. Normalised concentration of oxides of nitrogen in the exhaust of the Garrett Honeywell GTCP85 APU gas turbine engine as a function of biofuel blend ratio and for three different engine conditions. Data is normalized with respect to NOx emissions for Jet A-1 under no load. Key: Blue NL (no load); Red ECS (environmental control system); Green MES (main engine start). Uncertainty on individual NOx measurement points is estimated to be +/- 5ppm. Least squares linear trend lines are indicated for reference.

6 Discussion

Engine parameters: To a first order approximation, the rate of decrease in the mass fuel flow to the engine scales in proportion to the specific energy of the fuel adjusted for blend ratio, such that the rate of energy input to the engine remains constant for a given engine condition. This trend of reduced fuel flow with increasing fuel specific energy density is consistent with data previously reported in the literature.

The marginal drop in EGT and the reduction in shaft speed that are observed with increasing biofuel blend ratio are statistically significant. However, the author is not aware of any data within the literature that supports this observation. There are a number of possible theoretical explanations but the increase in the fuel H/C ratio and the concurrent nature of these effects are confounding factor that may also be connected, Hence further analysis is necessary to develop an understanding which will then be reported as an addendum.

No adverse effects were detected in engine parameters when using the ITAKA MCA batch biofuel at any blend ratio including those above the 50% certification limit.

Emissions of UHC: As a product of incomplete combustion, the quantitative emission of UHC is strongly dependent upon engine type, combustion technology and is generally related to the combustion efficiency of the engine, Physical factors that can influence the level of UHC emissions include: fuel air ratio, temperature and pressure at the combustor inlet, fuel injection / atomisation / mixing in the combustion primary zone and of course engine condition (production is lowest at high power and highest at idle).

From a comparison of data from a number of alternative fuels test programs, it quickly become apparent that evidence is often widely conflicting with some tests showing a reduction of up to ~44% [DeWitt et al, 2008] with other tests showing an increase of similar magnitude [Rahmes et al, 2009]. Whilst these percentage changes may seem alarming it must be born in mind that that emission levels are only significant at low power setting and even here they are typically very low (~10 ppm). Hence great care should be taken when drawing firm conclusions from the inter-comparison of results.

Within the SWAFEA project, the difficult task for forecasting UHC emissions in a generic manor and for a generic alternative fuel was reliant upon the limited published data that was available at the time. It was suggested that in a predicted future fleet scenario powered by a 50:50 blended fuel, UHC emissions for GE engines would show an increase (~20%), whilst for Rolls Royce engines there would be and a null change. Four years further on from SWAFEA the body of literature from which to draw is considerably greater, and the consensus averaged over a larger number of reported data both positive and negative is converging towards a null or slightly negative change in UHC emissions. The mechanisms behind this change are uncertain. Suggested mechanisms include: the reduction in fuel aromatics promotes the clean burn characteristics and combustion efficiency, the increase in hydrogen availability (through increased H/C ratio) increases the OH radical pool, amongst others.

Experimental data from the combustion of the ITAKA MCA batch biofuel in the Garret APU gas turbine is consistent with this assessment that a null change in UHC is most probable. The data further demonstrate the sensitivity of the measurement to ambient parameters that are difficult to correct and add to measurement uncertainty beyond instrument error.

Emissions of CO: As a product of incomplete combustion, the quantitative emission of CO have much in common with the emissions of UHC and are strongly dependent upon engine type, combustion technology and is generally related to the combustion efficiency of the engine, Physical factors that can influence the level of UHC emissions again include: fuel air ratio, temperature and pressure at the combustor inlet, fuel injection / atomisation / mixing in the combustion primary zone and engine condition, but is particularly susceptible to effects caused by the fuel injectors.

From a comparison of data from a number of alternative fuels test programs, it is clear that CO emissions for alternative fuels are again diverse and widely conflicting data ranging from a 20% reduction over the LTO cycle for a PW rig burning neat SPK to an 8% increase from a CFM56-7B engine burning blends of HRJ has been reported. It has also been shown that CO emissions may be dependent on fuel aromatic content.

Within the SWAFEA project, it was suggested that for a predicted future fleet scenario powered by a 50:50 blended fuel, CO emissions for GE engines would show a slight increase (~4%), whilst for Rolls Royce engines there would be and a null change. However as previously noted, the body of literature from which to draw a considered estimation is now considerably greater, and the consensus averaged over a larger number of reported data is converging towards a similar null or slightly negative change in CO emissions. Again the mechanisms behind this change are uncertain but follow similar arguments to those suggested for UHC. In particular there are several kinetic studies that suggest OH radical is required for the rapid oxidation of CO, and the addition of small quantities of H_2 has been found to reduce CO emission from a gas turbine [eg. Frenillot et al, 2009], presumably through an increased OH radical concentration.

Experimental data from the combustion of the ITAKA MCA batch biofuel in the Garret APU gas turbine is consistent with this assessment. The data further demonstrate that the small decrease in the emission of CO with an increasing fraction of MCA biofuel is a linear relation (with reasonable confidence), and that it is present for all three engine conditions. Quantitatively, the magnitude of the decrease in the emission of CO observed here is greater than the expected decrease (ie. in relation to the literature consensus value) but is not out of bounds.

Emissions of NOx: In a gas turbine engine, nitrogen oxides can be formed via two mechanisms: oxidation of free air nitrogen in the combustion process often termed ‘thermal NOx’, and oxidation of the fuel bound nitrogen or ‘organic NOx’. The oxidation of fuel bound nitrogen is highly efficient but quantitatively it is much less significant in comparison to thermal NOx. Nevertheless, it is worth noting since the concentration of fuel bound nitrogen is much reduced in HEFA biofuels due to the hydro-processing production step, and hence organic NOx emissions are not expected.

General trends for the emission of thermal NOx are difficult to establish since it is strongly depend upon engine type and combustion technology, with newer combustor technologies (lean FAR technologies such as TAPS) having made possible significant progress in the reduction of NOx emissions.

Physical factors that can strongly influence the level of NOx emissions include: flame temperature, fuel air ratio, temperature and pressure at the combustor inlet, flame residence time, and engine condition (production is highest at high power and lowest at idle). In addition NOx emissions decrease exponentially with increasing water or specific humidity, a property that is utilised in non-aviation gas turbines as a reduction strategy.

It was suggested within the SWAFEA project that for a future fleet scenario powered by a 50:50 generic alternative fuel, NOx emissions for GE engines would show a slight reduction (~5%), whilst for Rolls Royce engines there would be a slight increase (~5%). However these estimates were based on a very limited datasets from the small number of publications that were available at the time. Since that early review the body of work in the literature has much increased. There remains a wide range of estimates with a small number of authors have published results that show NOx emissions may be appreciably reduced with alternative fuels, even by as much as 12% [Timko et al, 2010], and engine performance simulations using an optimised chemical reactors network are consistent with this finding [ECATS, 2012]. However, the full cross section of engine technology has not been evaluated, and the newer low NOx combustor designs are notably absent from the literature. Overall the consensus of opinion drawn from the available data remains variable and there seems little basis for deviating from the range previously proposed within SWAFEA.

Theoretical mechanisms to support a change in NOx emission are complex, can be positive or negative and include: a marginally reduced flame temperature due to the reduced level of unsaturated and aromatic compounds [Goodger, 1980]; an increased flame residency time; and an slight increase in the specific humidity within the combustor due to the increased H/C ratio in the fuel which increases the concentration of the OH radical pool.

Experimental data in this report for the combustion of the ITAKA MCA batch biofuel in the Garret APU gas turbine is consistent with this assessment; the data indicates no significant change in the emission of NOx with increasing MCA biofuel blend ratio. The data demonstrate a relatively weak sensitivity to ambient humidity, but no dependency on ambient temperature or pressure, and measurement uncertainty is dominated by instrument error.

Emissions of PM: Perhaps the most notable impact of HEFA and other low aromatic / high iso-alkane fuels and fuel blends on engines emissions is the very strong reduction of particulate matter which gives rise to a much reduced smoke number. Evidence that the reduction in primary fine particulate matter (soot) occurs due to the lower aromatics content in the fuel is quite firm, and aromatics are attributed as the class of compounds that primarily influence the tendency to form soot during combustion [Timko et al, 2010], although it is suggested that fuel hydrogen content may be a more fundamental parameter that is independent of molecular structure [Moses, 1984].

For a given fuel, the soot formation process is largely determined by aspects of the combustor design that control stoichiometry and mixing in the primary zone. Hence it is generally specific to the combustor and engine design. There have been a number of studies on the combustion and emission characteristics of alternative fuels in a gas turbine engine: Timko et al (2010) compared the emissions from JP8, a synthetic GTL, and a composite blend using a PW308 gas turbine engine; Corporan et al (2011) similarly investigated the emission characteristics of JP8, a GTL, and composite blends using both a T63 turbo shaft engine and in a research combustor. Both groups report a dramatic reduction in the concentration and size of particulates for GTL in comparison to

JP8. Lobo et al (2011) compare the emissions for a FT fuel, a FT/Jet A-1 blend and several FAME biofuel/Jet A-1 blends in relation to conventional Jet A-1 on a CFM56-7B commercial jet engine. They also report significant reductions in the emissions of PM mass and number with FT fuels, which they attribute to low aromatic content and high hydrogen/carbon ratio. Additionally, DeWitt et al (2008) in an investigation of fuel composition, material compatibility and its relation to emission characteristics showed that PM emissions increase with both increasing fuel aromatic content and increased aromatic molecular weight when evaluated in a T63 turbo shaft engine. This increase in PM emissions they attributed to an increase in soot precursors. Similarly the AAFEX experimental study reports concentrations of soot at the engine exit nozzle may be reduced by 30% to 90%.

Whilst we can conclude with reasonably high confidence that HEFA and other low aromatic / high iso-alkane fuels and fuel blends exhibit significantly lower PM emissions in comparison to Jet A-1, our understanding of the soot inception process within a gas turbine combustor and for different fuels is generally weak. It has been postulated that the formation of soot nuclei is dominated by the condensation of fuel aromatics at lower combustor temperatures (i.e. idle) as these reactions proceed at a faster rate than the condensation of paraffinic compounds, whereas at higher combustor temperatures (i.e. high power) a mechanism involving the fragmentation and polymerization of both aromatics and paraffinic species is favoured [DeWitt et al, 2008]. Hence the formation of soot nuclei is much reduced for these fuels relative to Jet A-1 due to the near zero aromatic content and this effect is particularly evident at low power. However the consecutive stages of soot growth through surface mediated reactions and particle coagulation to form nano- to micron-sized particles is more difficult to model with acetylene, ionic species and benzene all having been proposed as key gaseous species. This is significant since soot particles accumulate most of their mass from surface reactions, and the mechanisms for surface growth are also poorly understood.

Experimental data in this report for the combustion of the ITAKA MCA batch biofuel in the Garret APU gas turbine is consistent with this assessment. The engine smoke number shows an approximately linear decrease with increasing MCA fuel blend fraction. All three engine conditions showing a similar rate of decrease. Detailed characterisation of the nvPM component showed that both the number based EI and the mass based EI exhibit an almost linear reduction with an increasing proportion of MCA biofuel. Although the data also show evidence that the mass based emissions index asymptote towards a fixed and maximum reduction at the higher fuel blend ratios in excess of 80%. Again, this was the case for each of the engine conditions. Furthermore, and in agreement with DeWitt et al (2008), the magnitude of the nvPM EIn and EIm reductions were highest at the MES engine condition, followed by ECS, and then the NL engine condition for all of the fuel blends. Specifically, for the 100% MCA biofuel fuel, the percent reductions in EIn were 74% (MES) > 66% (ECS) > 61% (NL), whereas the corresponding percent reductions for EIm were 93% (MES) > 91% (ECS) > 88% (NL).

The ultrafine nvPM emissions exhibited a lognormal size distribution, which narrows and shifts the geometric mean diameter to smaller sizes as the proportion of MCA biofuel in the fuel blend is increased. These data are consistent with those reported for other gas turbine engines burning conventional and alternative fuels [Lobo et al, 2011; Cain et al, 2013; Lobo et al, 2015; amongst others].

Emissions of CO_2 and H_2O: Though not classified as pollutants and absent from the ICAO emissions database, CO_2 and H_2O are emission species that are relevant to atmospheric and climate modelling are so are included within this analysis for completeness. The emission index for each of these species is readily calculated from the fuel H/C ratio mass balance with the assumption of 100% combustion.

Two of the most notable properties of the MCA batch biofuel in relation to the baseline Jet A-1 are the increase in energy density, and the increase in H/C ratio. In this task the increase in energy density has been shown to result in a corresponding reduction in fuel flow such that the rate at which energy remains approximately constant. This result is consistent with other data in the literature. Whereas the increase in H/C ratio is a fuel property that arises from differences in fuel chemistry, and the MCA fuel contain a higher proportion of saturated compounds (n-paraffins and iso-paraffins) and a much reduced aromatic content in comparison to the baseline Jet A-1.

The shift in these two properties produces a change in both the overall and relative emissions of CO_2 and H_2O: Firstly, the increase in H/C ratio produces an increase in the $EI(H_2O)$ and a decrease in the $EI(CO_2)$ as enumerated below. Secondly the EIs of the MCA biofuel must be scaled to take into consideration the reduction in fuel flow to produce an EI with units g/kg Jet A-1 equivalent.

Baseline Jet A-1 fuel: $EI(H_2O)$ = 1229 g/kg fuel; $EI(CO_2)$ = 3160 g/kg Jet A-1 fuel

MCA batch fuel: $EI(H_2O)$ = 1333 g/kg fuel; $EI(CO_2)$ = 3044 g/kg Jet A-1(eq) fuel

Hence the hypothetically operation of the fleet on a 50:50 blend of the ITAKA MCA batch biofuel would reduce the overall emissions of CO_2 by ~ 1.85% and increase the overall emissions of H_2O by ~ 4.25% from a tank to wake perspective.

These figures are broadly in line with those estimated in the SWAFEA project for a generic alternative fuel use scenario (emission of CO_2 reduced by ~1.7%, and emission of H_2O increased by ~3.7%) [SWAFEA, 2011].

Experimental measurement of the concentration and calculated EI's for CO_2 are consistent with the theoretically emissions calculated from the H/C ratio.

In relation to the climate impact of aviation, the relative increase in the emission of H_2O requires analysis in relation to the propensity to form contrails and induced cirrus. Whilst tropospheric water is relatively short lived the potential consequence of increased stratospheric water in polar routes does require further consideration.

Emissions of SO_2: Typically, Jet A-1 in the EU has a sulphur content of <500 ppm with an upper specification limit of 3000ppm, whilst equivalent levels in HEFA based biofuels are near zero due to the hydro-processing production step. Specific to this task, the baseline Jet A-1 fuel sulphur content was ~ 330ppm and the MCA batch biofuel was < 3ppm. From simple mass balance, a strong reduction in SOx emissions can be the only result, with a similarly strong reduction in volatile particulate matter and secondary particles formation: The emission of sulphates as combustion products can be directly related to fuel composition and estimated from blend fraction alone: The operation of the commercial fleet on a 50:50 MCA type biofuel/Jet A-1 blend would result in a corresponding 50% reduction in global emissions of sulphates.

Fuel flow based emission estimates: Emissions modelling software such as Advanced Emission Model 3 (AEM3) use fuel flow within a surrogate procedure to estimate in-flight emissions of CO, NOx and UHC. The Boeing Fuel Flow Method 2 (BFFM2) is one such commonly used empirical procedure that uses as its base fuel flow and standard ICAO data, but also includes ambient pressure, temperature, relative humidity and Mach number. Within a European setting, Eurocontrol have implemented a modified version of BFFM2 that contains a slightly different specific humidity correction factor within its AEM3 emissions calculations. Details on the implementation of this method are given in Jelinek et al, 2004.

The fuel flow method of emissions calculation is relevant to the current task only in as much as a change in the fuel properties might bring about a shift in the ICAO engine database of EI's and therefore perturbate the emissions calculation. The parameters of concern are fuel flow and EI's for CO, UHC, and NOx, all other parameters remain equal.

Data reported here has shown that the change in the emission indices for the species CO, UHC, NOx with increasing biofuel blend fraction is either null or edging towards a modest decrease with increasing blend ratio. And whilst this does not guarantee that this will be the case for all gas turbine hardware, it is nevertheless indicative of what might be expected. Similarly the reduction in the fuel flow with increasing biofuel blend ratio has been shown here and elsewhere to scale with the energy content of the fuel, which for a 50% blend fraction represents a shift of around 1%

Consequently we can cautiously conclude that fleet emission estimates calculated by the fuel flow method are reasonably independent of the biofuel blend ratio, and any perturbation will be small and in any case bounded by the uncertainty that is inherent within the BFFM2 method.

7 Conclusions

Variations in jet fuel properties can have a significant influence on the engine cycle and performance of a gas turbine which can then perturb the combustion species that are emitted in the exhaust. In this task we have characterised the performance and emissions from the combustion of the ITAKA MCA batch biofuel in a small gas turbine and in relation to a Jet A-1 baseline. Similar testing on a commercial aircraft main engine would have demanded an order of magnitude increase in cost for very little gain in data, since absolute quantitative data is not relevant and fuel chemistry has a more significant impact on qualitative emissions than a shift in gas turbine hardware.

The ITAKA MCA biofuel sourced from SkyNRG was derived from used cooking oil, whilst a straight run Jet A-1 sourced from within the UK was used as both baseline and blend component fuel. A complete GC x GC analysis of the MCA biofuel and baseline Jet A-1 provided a comprehensive qualitative and quantitative chemical breakdown of the fuel groupings, and showed that the aromatic, alkane and cyclo-paraffinic structures in the two fuels are significantly different.

A total of seventeen different blend ratios in the range from 100% Jet A-1 up to 100% ITAKA MCA biofuel have been evaluated. This is the largest most comprehensive dataset in the literature. It covers the range of blends beyond the current ASTM 50% certification limit (additional subtask 1) which may be important in future certification, and allows performance and emission trends to be assessed with statistically significant confidence.

The engine performance data showed that there is a reduction in fuel flow with increasing biofuel blend fraction. The reduction in fuel flow scales in proportion to the mass corrected specific energy density of the fuel blend that enters the engine. This data is consistent with other data in the literature.

A marginal drop in EGT and a slight reduction in engine shaft speed were also observed with increasing biofuel blend ratio. These trends are statistically significant. However, the author is not aware of any data within the literature that supports this observation and further analysis is necessary.

For particulate emissions, a clear and pronounced reduction in the SAE smoke number was observed with increasing biofuel blend ratio. The reduction in smoke number with blend ratio was approximately linear, and the rate of reduction with blend ratio was approximately the same for the three engine conditions. The data are consistent with the consensus opinion that smoke number primarily scales with the aromatic content of the fuel.

A full characterisation on the nvPM component of the smoke has also been developed (additional subtask 2) using the state of the art North American Reference System. These data showed that to a good first order approximation both the number and mass based emission indices reduce linearly with increasing MCA blend fraction, although the data also show evidence that the mass based emissions index asymptote towards a fixed and maximum reduction at the higher fuel blend ratios in excess of 80% MCA. The magnitude of these reductions in nvPM emissions are greatest for higher engine powers (up to a 93% reduction in mass and a 74% reduction in number). These reductions are accompanied by a corresponding shift in the geometric mean diameter to smaller size, and an increasingly mono-disperse size distribution. Data are consistent with other data reported in the literature.

For gaseous emissions, no statistically significant change in the emissions of NOx or UHC was observed with increasing MCA blend fraction on this hardware (although the trend line does imply the hidden presence of a small reduction). In contrast a small but statistically significant reduction in CO was observed with increasing MCA biofuel fraction. These data are consistent with the range of data reported elsewhere and illustrate the relatively small scale perturbation in the emission of these gaseous species that is expected.

The emissions of PM, UHC and CO are all related in that they belong to a grouping loosely defined as products of incomplete combustion. However the underlying mechanisms that lay behind their production and destruction are clearly different. For example, the reduction in fuel aromatics may have a significant effect on PM but the effect is not transferable to other species within the grouping, and significant gaps in the knowledgebase that maps fuel properties to emissions still exist.

No adverse effects were detected with the use of the ITAKA MCA batch biofuel at any blend ratio including those above the 50% certification limit.

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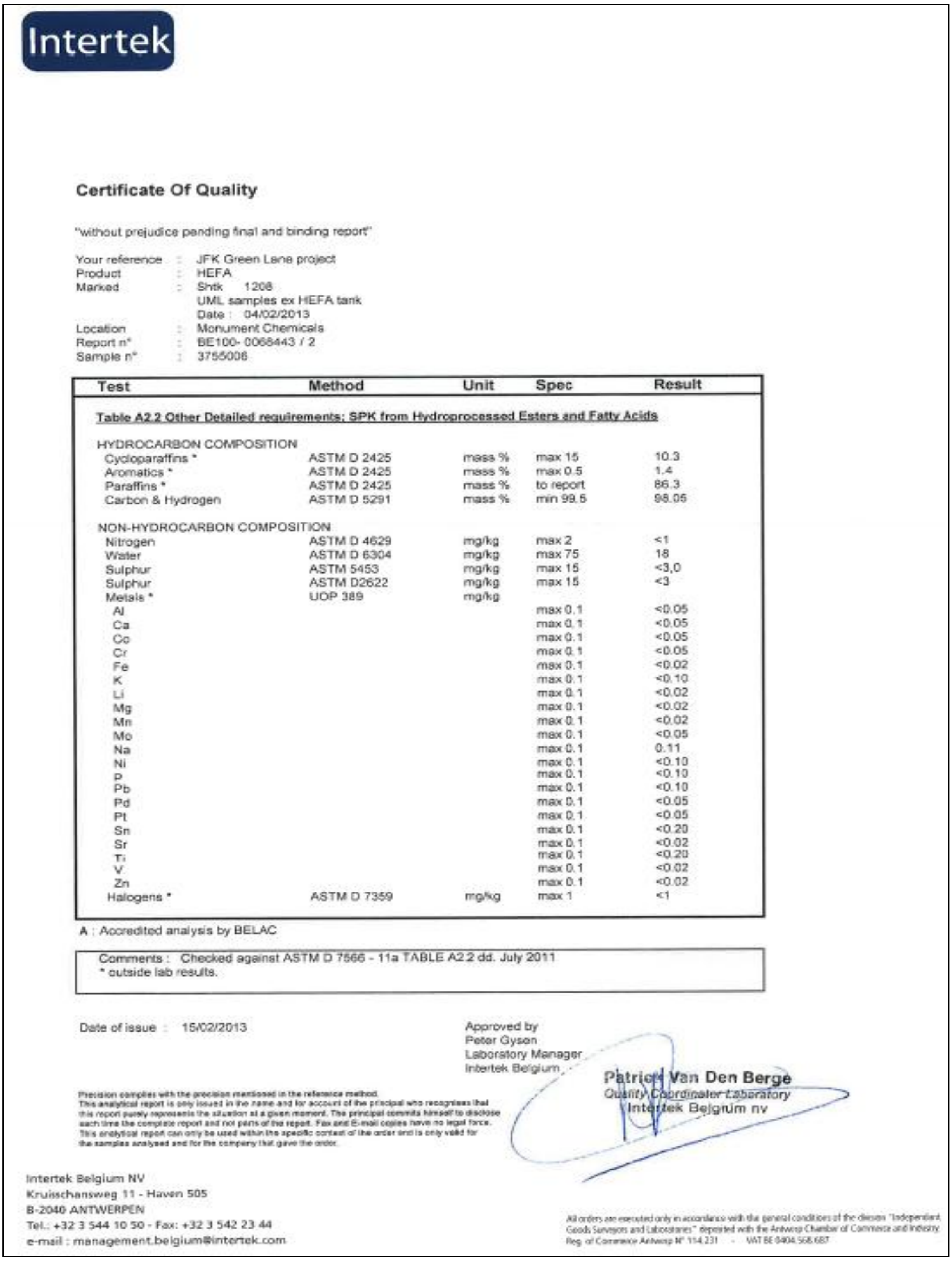
Annex A Fuel certificates of quality

In the follow are the certificates of fuel quality measured by an independent third party laboratory.

1) **ITAKA MCA ‘off-spec’ batch HEFA biofuel (Netherlands Intertek analysis)**



Intertek

Certificate Of Quality

"without prejudice pending final and binding report"

Your reference : JFK Green Lane project
Product : HEFA
Marked : Shtk 1208
UML samples ex HEFA tank
Date : 04/02/2013
Location : Monument Chemicals
Report n° : BE100- 0066443 / 2
Sample n° : 3755006

Test	Method	Unit	Spec	Result
<u>Table A2.2 Other Detailed requirements: SPK from Hydroprocessed Esters and Fatty Acids</u>				
HYDROCARBON COMPOSITION				
Cycloparaffins *	ASTM D 2425	mass %	max 15	10.3
Aromatics *	ASTM D 2425	mass %	max 0.5	1.4
Paraffins *	ASTM D 2425	mass %	to report	86.3
Carbon & Hydrogen	ASTM D 5291	mass %	min 99.5	98.05
NON-HYDROCARBON COMPOSITION				
Nitrogen	ASTM D 4629	mg/kg	max 2	<1
Water	ASTM D 6304	mg/kg	max 75	18
Sulphur	ASTM 5453	mg/kg	max 15	<3,0
Sulphur	ASTM D2622	mg/kg	max 15	<3
Metals *	UOP 389	mg/kg		
Al			max 0.1	<0.05
Ca			max 0.1	<0.05
Co			max 0.1	<0.05
Cr			max 0.1	<0.05
Fe			max 0.1	<0.02
K			max 0.1	<0.10
Li			max 0.1	<0.02
Mg			max 0.1	<0.02
Mn			max 0.1	<0.02
Mo			max 0.1	<0.05
Na			max 0.1	0.11
Ni			max 0.1	<0.10
P			max 0.1	<0.10
Pb			max 0.1	<0.10
Pd			max 0.1	<0.05
Pt			max 0.1	<0.05
Sn			max 0.1	<0.20
Sr			max 0.1	<0.02
Ti			max 0.1	<0.20
V			max 0.1	<0.02
Zn			max 0.1	<0.02
Halogens *	ASTM D 7359	mg/kg	max 1	<1

A : Accredited analysis by BELAC

Comments : Checked against ASTM D 7566 - 11a TABLE A2.2 dd. July 2011
* outside lab results.

Date of issue : 15/02/2013

Approved by
Peter Gyson
Laboratory Manager
Intertek Belgium

Patrick Van Den Berge
Quality Coordinator Laboratory
Intertek Belgium nv

Precision complies with the precision mentioned in the reference method.
This analytical report is only issued in the name and for account of the principal who recognises that this report purely represents the situation at a given moment. The principal commits himself to disclose each time the complete report and not parts of the report. Fax and E-mail copies have no legal force.
This analytical report can only be used within the specific context of the order and is only valid for the samples analysed and for the company that gave the order.

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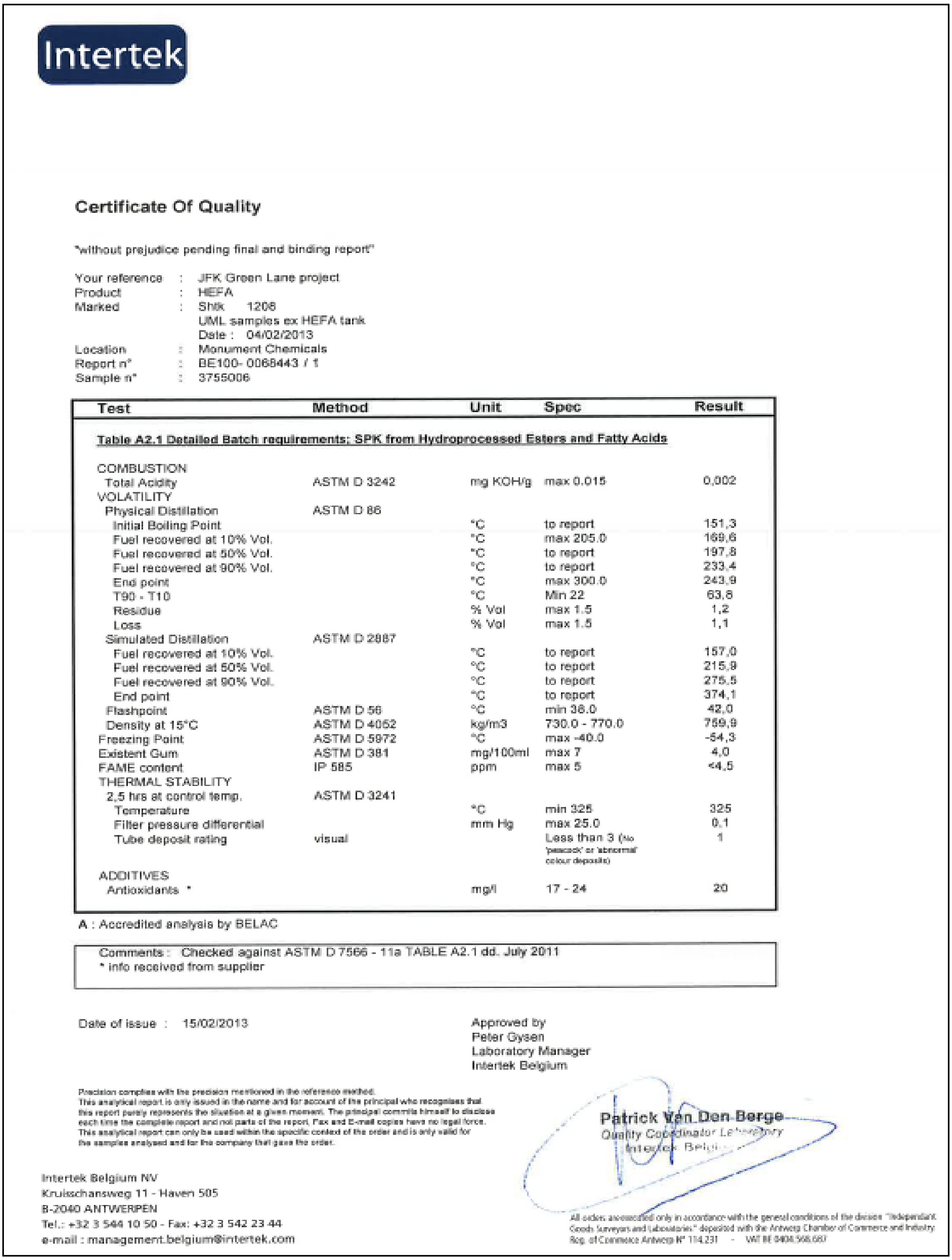

Intertek

Certificate Of Quality

"without prejudice pending final and binding report"

Your reference : JFK Green Lane project
Product : HEFA
Marked : Shtk 1208
UML samples ex HEFA tank
Date : 04/02/2013
Location : Monument Chemicals
Report n° : BE100- 0068443 / 1
Sample n° : 3755006

Test	Method	Unit	Spec	Result
Table A2.1 Detailed Batch requirements; SPK from Hydroprocessed Esters and Fatty Acids				
COMBUSTION				
Total Acidity	ASTM D 3242	mg KOH/g	max 0.015	0,002
VOLATILITY				
Physical Distillation	ASTM D 86			
Initial Boiling Point		°C	to report	151,3
Fuel recovered at 10% Vol.		°C	max 205.0	169,6
Fuel recovered at 50% Vol.		°C	to report	197,8
Fuel recovered at 90% Vol.		°C	to report	233,4
End point		°C	max 300.0	243,9
T90 - T10		°C	Min 22	63,8
Residue		% Vol	max 1.5	1,2
Loss		% Vol	max 1.5	1,1
Simulated Distillation	ASTM D 2887			
Fuel recovered at 10% Vol.		°C	to report	157,0
Fuel recovered at 50% Vol.		°C	to report	215,9
Fuel recovered at 90% Vol.		°C	to report	275,5
End point		°C	to report	374,1
Flashpoint	ASTM D 56	°C	min 38.0	42,0
Density at 15°C	ASTM D 4052	kg/m3	730.0 - 770.0	759,9
Freezing Point	ASTM D 5972	°C	max -40.0	-54,3
Existent Gum	ASTM D 381	mg/100ml	max 7	4,0
FAME content	IP 585	ppm	max 5	<4,5
THERMAL STABILITY				
2,5 hrs at control temp.	ASTM D 3241			
Temperature		°C	min 325	325
Filter pressure differential		mm Hg	max 25.0	0,1
Tube deposit rating	visual		Less than 3 (No 'peacock' or 'abnormal' colour deposits)	1
ADDITIVES				
Antioxidants *		mg/l	17 - 24	20

A : Accredited analysis by BELAC

Comments : Checked against ASTM D 7566 - 11a TABLE A2.1 dd. July 2011
* info received from supplier

Date of issue : 15/02/2013

Approved by
Peter Gysen
Laboratory Manager
Intertek Belgium

Precision complies with the precision mentioned in the reference method. This analytical report is only issued in the name and for account of the principal who recognises that this report purely represents the situation at a given moment. The principal commits himself to disclose each time the complete report and not parts of the report. Fax and E-mail copies have no legal force. This analytical report can only be used within the specific context of the order and is only valid for the samples analysed and for the company that gave the order.

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2) ITAKA MCA ‘off-spec’ batch HEFA biofuel (UK Intertek analysis)

ANALYSIS	RESULTS	UNITS
Visual Appearance*	Fail[¥]	-
UOP938 Mercury Content*	1	ng/g
IP156 FIA Aromatics	1.8	% vol
IP156 FIA Olefins	0.4	% vol
IP156 FIA Saturates	97.8	% vol
D1322 Smoke point	>50	mm
D156 Saybolt Colour	+30	-
D3338 Specific Energy (S Corrected)	44.023	MJ/kg
D3948 Microsep	99	-
IP365 Density at 15°C	759	kg/
D4294 Sulphur	<0.	%
D86 Initial Boiling Point	148	°C
D86 05 % Recovered	163	°C
D86 10 % Recovered	169	°C
D86 20 % Recovered	177	°C
D86 30 % Recovered	184	°C
D86 40 % Recovered	191	°C
D86 50 % Recovered	198	°C
D86 60 % Recovered	206	°C
D86 70 % Recovered	214	°C
D86 80 % Recovered	224	°C
D86 90 % Recovered	235	°C
D86 95 % Recovered	242	°C
D86 Final Boiling Point	251	°C
D86 Loss	0.7	%
D86 Recovery	97.	%
D86 Residue	1.4	%
Nitrogen by combustion (MT/ELE/12)	<0.	mg
Sulphur by combustion (MT/ELE16)*	<0.	mg
IP 590 FAME in Jet by HPLC *	<1.	mg
D2386 Freeze point	-	°C
IP154 Copper Corrosion 2Hrs at 100°C	1b	-
IP170 Flashpoint	41.	°C
IP274 Conductivity at 21°C	0	pS/
IP289 Water Reaction Interface Rating	1b	-
IP30 Doctor Test	N	-
IP323 JFTOT Pressure Difference at 260°C	<1	m
IP323 JFTOT Visual tube rating at 260°C	<1	-
IP354 Total Acidity	0.0	mg
IP540 Existent Gum	1	mg
IP71 Kinematic Viscosity at -20°C	3.8	cSt
IP 406 Simulated Distillation*		
Initial Boiling Point	91.6	℃
Temp at 1.0% Recovery	105.4	℃
Temp at 2.0 % Recovery	117.0	℃
Temp at 3.0 % Recovery	125.8	℃
Temp at 4.0 % Recovery	133.2	℃
Temp at 5.0 % Recovery	139.8	℃
Temp at 6.0 % Recovery	141.4	℃
Temp at 7.0 % Recovery	142.2	℃
Temp at 8.0 % Recovery	143.2	℃
Temp at 9.0 % Recovery	146.4	℃
Temp at 10.0 % Recovery	150.4	℃

Temp at 11.0 % Recovery	151.0	℃
Temp at 12.0 % Recovery	151.6	℃
Temp at 13.0 % Recovery	155.4	℃
Temp at 14.0 % Recovery	157.0	℃
Temp at 15.0 % Recovery	158.4	℃
Temp at 16.0 % Recovery	159.8	℃
Temp at 17.0 % Recovery	162.6	℃
Temp at 18.0 % Recovery	163.8	℃
Temp at 19.0 % Recovery	164.6	℃
Temp at 20.0 % Recovery	165.2	℃
Temp at 21.0 % Recovery	165.4	℃
Temp at 22.0 % Recovery	166.0	℃
Temp at 23.0 % Recovery	166.4	℃
Temp at 24.0 % Recovery	167.2	℃
Temp at 25.0 % Recovery	167.8	℃
Temp at 26.0 % Recovery	170.4	℃
Temp at 27.0 % Recovery	173.2	℃
Temp at 28.0 % Recovery	173.8	℃
Temp at 29.0 % Recovery	174.0	℃
Temp at 30.0 % Recovery	174.8	℃
Temp at 31.0 % Recovery	177.4	℃
Temp at 32.0 % Recovery	178.8	℃
Temp at 33.0 % Recovery	180.0	℃
Temp at 34.0 % Recovery	181.4	℃
Temp at 35.0 % Recovery	182.4	℃
Temp at 36.0 % Recovery	184.8	℃
Temp at 37.0 % Recovery	186.2	℃
Temp at 38.0 % Recovery	186.8	℃
Temp at 39.0 % Recovery	187.4	℃
Temp at 40.0 % Recovery	188.0	℃
Temp at 41.0 % Recovery	188.4	℃
Temp at 42.0 % Recovery	189.2	℃
Temp at 43.0 % Recovery	190.0	℃
Temp at 44.0 % Recovery	192.6	℃
Temp at 45.0 % Recovery	195.2	℃
Temp at 46.0 % Recovery	195.6	℃
Temp at 47.0 % Recovery	196.2	℃
Temp at 48.0 % Recovery	197.0	℃
Temp at 49.0 % Recovery	198.8	℃
Temp at 50.0 % Recovery	199.8	℃
Temp at 51.0 % Recovery	201.0	℃
Temp at 52.0 % Recovery	202.2	℃
Temp at 53.0 % Recovery	203.4	℃
Temp at 54.0 % Recovery	205.4	℃
Temp at 55.0 % Recovery	206.6	℃
Temp at 56.0 % Recovery	207.4	℃
Temp at 57.0 % Recovery	208.0	℃
Temp at 58.0 % Recovery	208.8	℃
Temp at 59.0 % Recovery	209.6	℃
Temp at 60.0 % Recovery	210.4	℃
Temp at 61.0 % Recovery	212.6	℃
Temp at 62.0 % Recovery	215.0	℃
Temp at 63.0 % Recovery	215.8	℃
Temp at 64.0 % Recovery	216.2	℃
Temp at 65.0 % Recovery	217.4	℃
Temp at 66.0 % Recovery	218.8	℃

Temp at 67.0 % Recovery	219.8	℃
Temp at 68.0 % Recovery	221.0	℃
Temp at 69.0 % Recovery	222.4	℃
Temp at 70.0 % Recovery	224.2	℃
Temp at 71.0 % Recovery	226.0	℃
Temp at 72.0 % Recovery	226.8	℃
Temp at 73.0 % Recovery	227.6	℃
Temp at 74.0 % Recovery	228.6	℃
Temp at 75.0 % Recovery	229.6	℃
Temp at 76.0 % Recovery	231.0	℃
Temp at 77.0 % Recovery	233.6	℃
Temp at 78.0 % Recovery	235.0	℃
Temp at 79.0 % Recovery	235.6	℃
Temp at 80.0 % Recovery	236.8	℃
Temp at 81.0 % Recovery	238.2	℃
Temp at 82.0 % Recovery	239.2	℃
Temp at 83.0 % Recovery	240.8	℃
Temp at 84.0 % Recovery	242.6	℃
Temp at 85.0 % Recovery	244.6	℃
Temp at 86.0 % Recovery	245.6	℃
Temp at 87.0 % Recovery	246.8	℃
Temp at 88.0 % Recovery	248.0	℃
Temp at 89.0 % Recovery	249.8	℃
Temp at 90.0 % Recovery	252.8	℃
Temp at 91.0 % Recovery	253.8	℃
Temp at 92.0 % Recovery	254.6	℃
Temp at 93.0 % Recovery	256.2	℃
Temp at 94.0 % Recovery	257.8	℃
Temp at 95.0 % Recovery	260.0	℃
Temp at 96.0 % Recovery	261.8	℃
Temp at 97.0 % Recovery	263.0	℃
Temp at 98.0 % Recovery	264.0	℃
Temp at 99.0 % Recovery	265.4	℃
Final Boiling Point	266.4	℃
JFTOT Break Point Analysis		
IP323 JFTOT Break Point	>380	-
IP323 JFTOT Test Temp	280	℃
IP323 JFTOT Pressure Difference	<1	mmHg
IP323 JFTOT Visual tube rating	<1	-
IP323 JFTOT Test Temp	290	℃
IP323 JFTOT Pressure Difference	<1	mmHg
IP323 JFTOT Visual tube rating	1	-
IP323 JFTOT Test Temp	300	℃
IP323 JFTOT Pressure Difference	<1	mmHg
IP323 JFTOT Visual tube rating	<1	-
IP323 JFTOT Test Temp	320	℃
IP323 JFTOT Pressure Difference	<1	mmHg
IP323 JFTOT Visual tube rating	<1	-
IP323 JFTOT Test Temp	340	℃
IP323 JFTOT Pressure Difference	<1	mmHg
IP323 JFTOT Visual tube rating	<1	-
IP323 JFTOT Test Temp	360	℃
IP323 JFTOT Pressure Difference	<1	mmHg
IP323 JFTOT Visual tube rating	<1	-
IP323 JFTOT Test Temp	380	℃

IP323 JFTOT Pressure Difference	<1	mmHg
IP323 JFTOT Visual tube rating	<1	-
(MT/ELE/15) ICP-MS Elemental Analysis*		
Aluminium	5	ng/g
Arsenic	<	ng/g
Barium	<	ng/g
Calcium	<	ng/g
Chromium	<	ng/g
Copper	<	ng/g
Iron	3	ng/g
Lead	<	ng/g
Magnesium	6	ng/g
Manganese	<	ng/g
Molybdenum	1	ng/g
Nickel	<	ng/g
Phosphorus	1	ng/g
Potassium	1	ng/g
Selenium	7	ng/g
Sodium	<	ng/g
Tin	<	ng/g
Titanium	<	ng/g
Vanadium	<	ng/g
Zinc	<	ng/g

3) UK sourced baseline Jet A-1 (Intertek UK analysis)

ANALYSIS	RESULTS	UNITS
Visual Appearance*	Fail[¥]	-
UOP938 Mercury Content*	1	ng/g
IP156 FIA Aromatics	19.2	% vol
IP156 FIA Olefins	0.6	% vol
IP156 FIA Saturates	80.2	% vol
D1322 Smoke point	23.0	mm
D156 Saybolt Colour	+27	-
D1840 Naphthalenes	1.95	% vol
D3338 Specific Energy (S Corrected)	43.153	MJ/kg
D3948 Microsep	89	-
IP365 Density at 15°C	805.3	kg/m^3
D4294 Sulphur	0.033	% mass
D86 Initial Boiling Point	149.9	°C
D86 05 % Recovered	159.4	°C
D86 10 % Recovered	163.8	°C
D86 20 % Recovered	170.3	°C
D86 30 % Recovered	176.2	°C
D86 40 % Recovered	183.3	°C
D86 50 % Recovered	190.4	°C
D86 60 % Recovered	199.4	°C
D86 70 % Recovered	210.0	°C
D86 80 % Recovered	222.2	°C
D86 90 % Recovered	236.4	°C
D86 95 % Recovered	247.6	°C

D86 Final Boiling Point	259.1	℃
D86 Loss	0.9	% vol
D86 Recovery	98.0	% vol
D86 Residue	1.1	% vol
Nitrogen by combustion (MT/ELE/12)	2.4	mg/kg
Sulphur by combustion (MT/ELE16)*	310	mg/kg
IP 590 FAME in Jet by HPLC *	<1.3	mg/kg
D2386 Freeze point	-59.0	℃
IP154 Copper Corrosion 2Hrs at 100°C	1a	-
IP170 Flashpoint	42.0	℃
IP274 Conductivity at 21°C	251	pS/
IP289 Water Reaction Interface Rating	1b	-
IP30 Doctor Test	P	-
IP323 JFTOT Pressure Difference at 260°C	1	mm
IP323 JFTOT Visual tube rating at 260°C	<1	-
IP342 Mercaptan sulphur	<0.00	%
IP354 Total Acidity	0.008	mg
IP540 Existent Gum	<1	mg/1
IP71 Kinematic Viscosity at -20°C	3.521	cSt
IP 406 Simulated Distillation*		
Initial Boiling Point	105.4	℃
Temp at 1.0% Recovery	117.0	℃
Temp at 2.0 % Recovery	125.8	℃
Temp at 3.0 % Recovery	132.0	℃
Temp at 4.0 % Recovery	133.8	℃
Temp at 5.0 % Recovery	137.2	℃
Temp at 6.0 % Recovery	139.0	℃
Temp at 7.0 % Recovery	140.0	℃
Temp at 8.0 % Recovery	142.0	℃
Temp at 9.0 % Recovery	143.8	℃
Temp at 10.0 % Recovery	145.4	℃
Temp at 11.0 % Recovery	147.0	℃
Temp at 12.0 % Recovery	150.2	℃
Temp at 13.0 % Recovery	150.8	℃
Temp at 14.0 % Recovery	151.2	℃
Temp at 15.0 % Recovery	151.4	℃
Temp at 16.0 % Recovery	153.2	℃
Temp at 17.0 % Recovery	155.0	℃
Temp at 18.0 % Recovery	156.4	℃
Temp at 19.0 % Recovery	157.6	℃
Temp at 20.0 % Recovery	158.8	℃
Temp at 21.0 % Recovery	159.6	℃
Temp at 22.0 % Recovery	160.6	℃
Temp at 23.0 % Recovery	161.6	℃
Temp at 24.0 % Recovery	162.6	℃
Temp at 25.0 % Recovery	163.8	℃
Temp at 26.0 % Recovery	165.0	℃
Temp at 27.0 % Recovery	165.6	℃
Temp at 28.0 % Recovery	166.8	℃
Temp at 29.0 % Recovery	168.0	℃
Temp at 30.0 % Recovery	168.6	℃
Temp at 31.0 % Recovery	169.4	℃
Temp at 32.0 % Recovery	171.6	℃
Temp at 33.0 % Recovery	173.0	℃
Temp at 34.0 % Recovery	173.6	℃
Temp at 35.0 % Recovery	174.0	℃

Temp at 36.0 % Recovery	174.2	℃
Temp at 37.0 % Recovery	174.6	℃
Temp at 38.0 % Recovery	176.4	℃
Temp at 39.0 % Recovery	178.2	℃
Temp at 40.0 % Recovery	179.2	℃
Temp at 41.0 % Recovery	180.0	℃
Temp at 42.0 % Recovery	181.4	℃
Temp at 43.0 % Recovery	182.4	℃
Temp at 44.0 % Recovery	183.4	℃
Temp at 45.0 % Recovery	184.8	℃
Temp at 46.0 % Recovery	186.8	℃
Temp at 47.0 % Recovery	188.0	℃
Temp at 48.0 % Recovery	188.8	℃
Temp at 49.0 % Recovery	190.6	℃
Temp at 50.0 % Recovery	192.4	℃
Temp at 51.0 % Recovery	193.8	℃
Temp at 52.0 % Recovery	195.2	℃
Temp at 53.0 % Recovery	195.6	℃
Temp at 54.0 % Recovery	196.0	℃
Temp at 55.0 % Recovery	196.4	℃
Temp at 56.0 % Recovery	198.0	℃
Temp at 57.0 % Recovery	199.8	℃
Temp at 58.0 % Recovery	201.2	℃
Temp at 59.0 % Recovery	202.2	℃
Temp at 60.0 % Recovery	203.6	℃
Temp at 61.0 % Recovery	205.4	℃
Temp at 62.0 % Recovery	206.6	℃
Temp at 63.0 % Recovery	208.0	℃
Temp at 64.0 % Recovery	209.2	℃
Temp at 65.0 % Recovery	210.6	℃
Temp at 66.0 % Recovery	212.4	℃
Temp at 67.0 % Recovery	214.2	℃
Temp at 68.0 % Recovery	215.4	℃
Temp at 69.0 % Recovery	215.8	℃
Temp at 70.0 % Recovery	216.4	℃
Temp at 71.0 % Recovery	218.0	℃
Temp at 72.0 % Recovery	219.2	℃
Temp at 73.0 % Recovery	221.0	℃
Temp at 74.0 % Recovery	222.8	℃
Temp at 75.0 % Recovery	224.8	℃
Temp at 76.0 % Recovery	226.6	℃
Temp at 77.0 % Recovery	228.0	℃
Temp at 78.0 % Recovery	228.8	℃
Temp at 79.0 % Recovery	230.4	℃
Temp at 80.0 % Recovery	231.2	℃
Temp at 81.0 % Recovery	232.8	℃
Temp at 82.0 % Recovery	234.6	℃
Temp at 83.0 % Recovery	235.4	℃
Temp at 84.0 % Recovery	236.0	℃
Temp at 85.0 % Recovery	238.0	℃
Temp at 86.0 % Recovery	240.4	℃
Temp at 87.0 % Recovery	242.8	℃
Temp at 88.0 % Recovery	245.2	℃
Temp at 89.0 % Recovery	247.2	℃
Temp at 90.0 % Recovery	249.2	℃
Temp at 91.0 % Recovery	251.0	℃

Temp at 92.0 % Recovery	252.8	℃
Temp at 93.0 % Recovery	254.0	℃
Temp at 94.0 % Recovery	256.0	℃
Temp at 95.0 % Recovery	260.0	℃
Temp at 96.0 % Recovery	263.8	℃
Temp at 97.0 % Recovery	267.0	℃
Temp at 98.0 % Recovery	271.4	℃
Temp at 99.0 % Recovery	280.0	℃
Final Boiling Point	287.2	℃
JFTOT Break Point Analysis		
IP323 JFTOT Break Point	285	℃
IP323 JFTOT Test Temp	280	℃
IP323 JFTOT Pressure Difference	2	mmHg
IP323 JFTOT Visual tube rating	<1	-
IP323 JFTOT Test Temp	300	℃
IP323 JFTOT Pressure Difference	1	mmHg
IP323 JFTOT Visual tube rating	>4AP	-
IP323 JFTOT Test Temp	290	℃
IP323 JFTOT Pressure Difference	1	mmHg
IP323 JFTOT Visual tube rating	<4	-
IP323 JFTOT Test Temp	285	℃
IP323 JFTOT Pressure Difference	1	mmHg
IP323 JFTOT Visual tube rating	<1	-
(MT/ELE/15) ICP-MS Elemental Analysis*		
Aluminium	59.7	ng/g
Arsenic	<2	ng/g
Barium	<9	ng/g
Calcium	<5	ng/g
Chromium	<1	ng/g
Copper	<8	ng/g
Iron	3.52	ng/g
Lead	<5	ng/g
Magnesium	67.5	ng/g
Manganese	<10	ng/g
Molybdenum	1.31	ng/g
Nickel	<7	ng/g
Phosphorus	189	ng/g
Potassium	13.7	ng/g
Selenium	7.09	ng/g
Sodium	<20	ng/g
Tin	<1	ng/g
Titanium	<9	ng/g
Vanadium	<4	ng/g
Zinc	<9	ng/g

Note: A comparison of the data for the ‘off-spec’ ITAKA MCA batch HEFA biofuel produced by Intertek (UK) with that produced by Intertek (Netherlands), highlights the uncertainty in the analysis methodology and data.

Annex B Detailed fuel analysis

The ITAKA MCA fuel batch supplied by SkyNRG for the purpose of this task does not meet the ASTM D7566: It is incompliant with respect to aromatic content, which is greater than the maximum allowed under this specification. To achieve full compliance with D7566 this fuel required a further hydrotreating step to bring the aromatic content below 0.5%. This hydrotreating step was performed by UOP in the US, following which it was blended with Jet A-1, and shipped back to Amsterdam before being used in the KLM flight campaign between Schiphol and Bonaire in the Dutch Caribbean.

However for the purpose of this task, it was not possible to obtain sufficient experimental volumes of both hydrotreated MCA and the reference Jet A-1 with which it was blended due to logistical constraints. It has therefore been necessary to better characterise this 'out-of-spec' MCA fuel through a rigorous analytical approach to identify the chemical groups that are present and ensure that the deviation from specification is definable, not detrimental to the overall output of the study, and can be accounted for. The chemical characterisation of the MCA batch fuel and reference Jet A-1 fuel was determined by GC x GC analysis. GC x GC analysis has been shown to be in very good agreement with the traditional ASTM D2425 technique for measuring hydrocarbon group types in aviation fuels, and has the added benefit of improved resolution of paraffinic groups [Striebich et al, 2014]. A summary and detailed breakdown of the chemical makeup on a species by species basis is given in Figure 15 and Table 4.

The more significant criteria is that all emission measurements are made relative to a known and defined Jet A-1 baseline; measurements on an 'out of spec' biofuel of known properties is more informative than measurements of emissions from a blended fuel that contained a Jet A-1 of unknown characteristics.

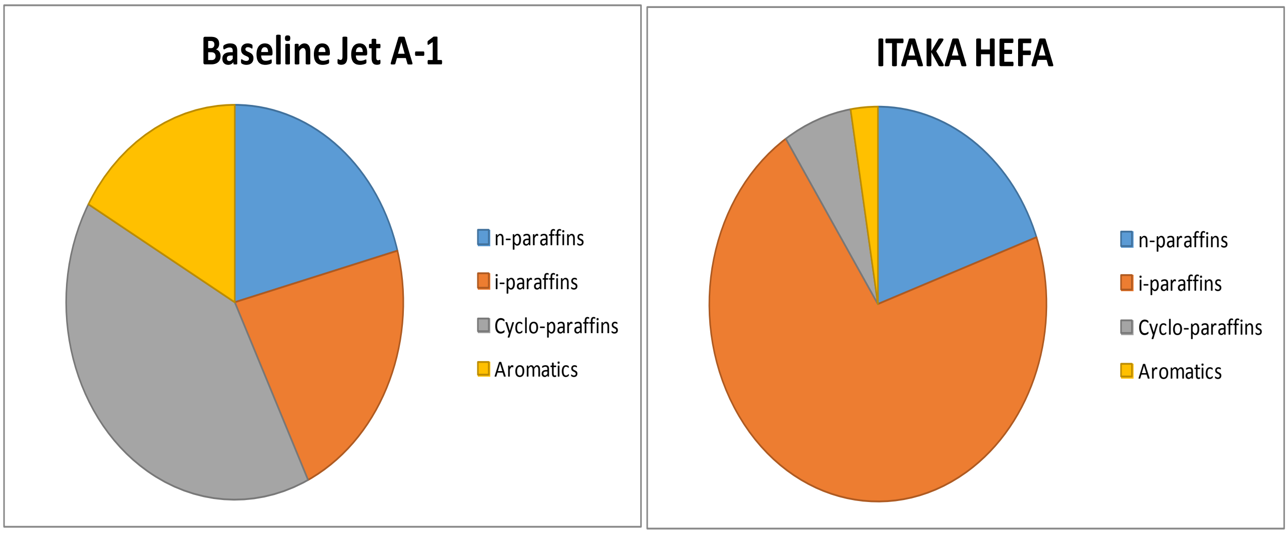

Figure 15. Schematic representation of the typical chemical composition for Jet A-1 and a HEFA type fuel.

Chemical group	Baseline Jet A-1	ITAKA MCA batch
n-paraffins	19.35	19.48
i-paraffins	20.57	71.35
naphthenes	37.65	6.58
alkyl benzenes	15.55	1.91
benzocycloparaffins	3.81	0.60
Naphthalenes	2.85	0.07
biphenyls/acenaphthenes	0.16	0.00
fluorenes	0.03	0.00
phenanthrenes	0.00	0.00
4 ring aromatics	0.00	0.00
polar unknown	0.02	0.01

Table 3. Summary table of chemical groups present in the ITAKA MCA batch fuel and reference Jet A-1 derived from GC x GC analysis.

Annex C Links

ITAKA

http://www.itaka-project.eu/

SWAFEA

www.swafea.eu (link no longer active

Alfabird

http://www.alfa-bird.eu-vri.eu/

CoreJetfuel

http://www.core-jetfuel.eu/

AAFEX

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110007202.pdf

APEX

http://nepis.epa.gov/Adobe/PDF/P1005KRK.pdf

ICAO aircraft engine emissions databank

https://easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank

[end of document]