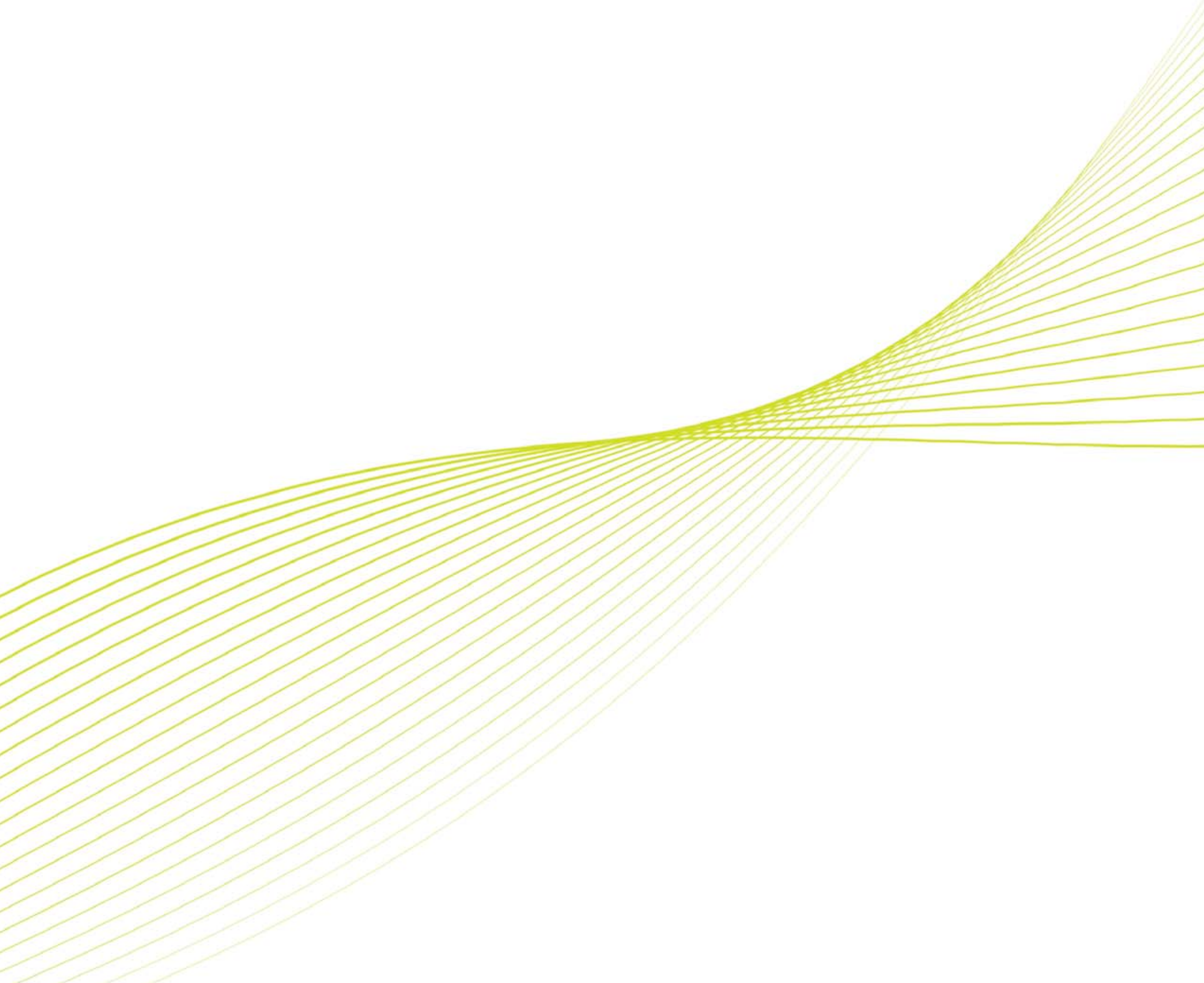
Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPK)

June 2009



Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes

Approbation

We, representing parties who participated in the aviation biofuels testing described in this document, note by our signatures that we concur with the "Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes" report.

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Evaluation of Bio-Derived Synthetic Paraffinic Kerosene (Bio-SPK)

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1.0 Introduction

It is of paramount importance that our industry must continue to progressively improve its environmental performance and lessen impacts to the global ecosystem, while continuing to reduce operating costs. Aviation recognizes these challenges must be addressed to ensure industry viability and is actively seeking to provide technologically driven solutions. Bio-derived jet fuel is a key element in the industry strategy to address these challenges. The signatories to this summary and many others have invested significant time and resources to further the research, development and commercialization of bio-derived jet fuel.

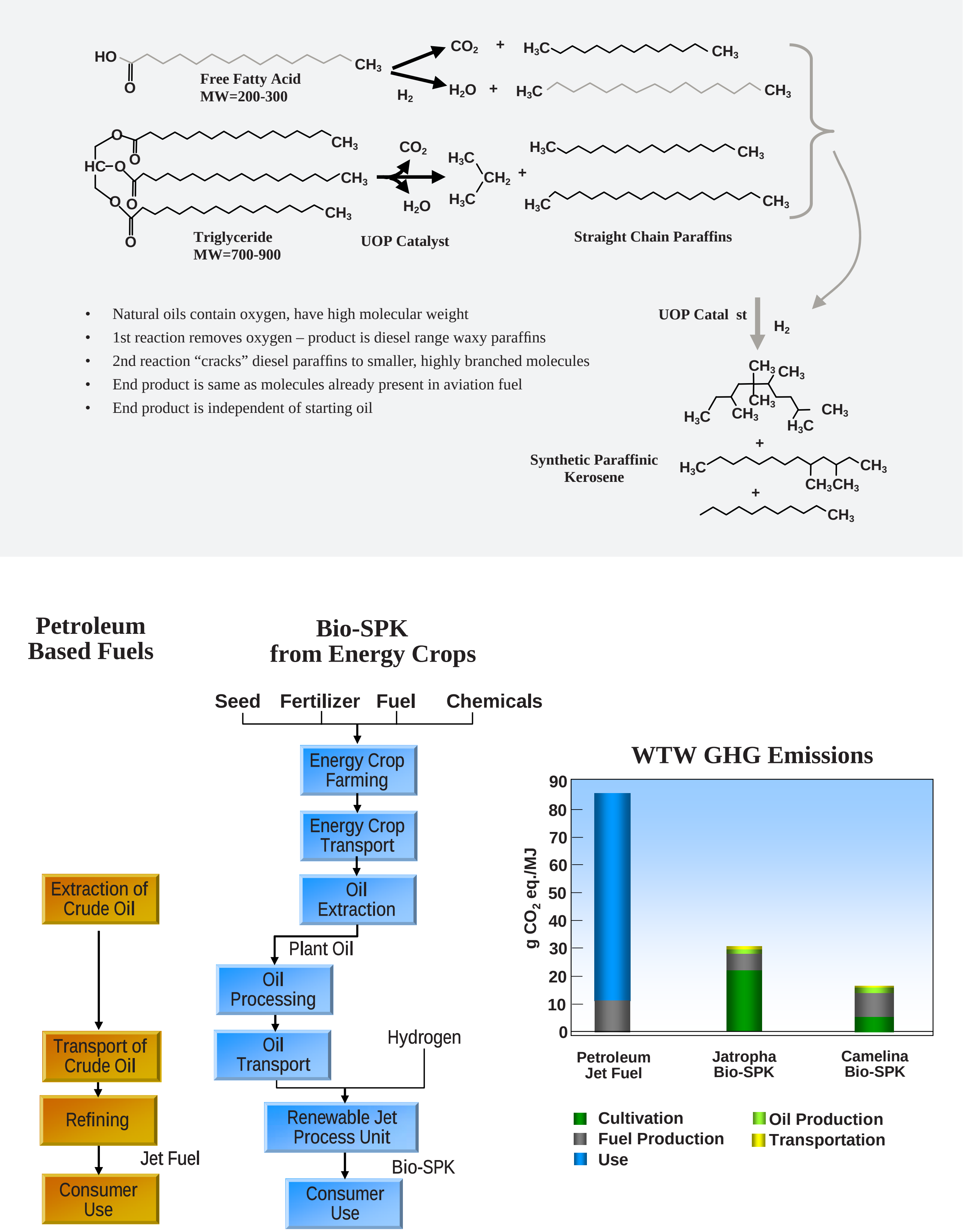
Virgin Atlantic paved the way with its proof of concept flight powered by biofuel in February 2008. Since that time, a broader range of fuels have become available that more closely replicate the performance characteristics of conventional kerosene jet fuel. Significant progress has been made in verifying the performance of Synthetic Paraffinic Kerosene (SPK) made from sustainable sources of bio-derived oils, that can be used in commercial aircraft at a blend ratio of up to 50 percent with traditional jet fuel (Jet A or Jet A-1). A cross-industry team consisting of Boeing, Honeywell/UOP, Air New Zealand (ANZ), Continental Airlines (CAL), Japan Airlines (JAL), General Electric, CFM, Pratt & Whitney, and Rolls-Royce participated in a series of tests flights with a bio-derived SPK (Bio-SPK) to collect data to support eventual certification of Bio-SPK jet fuels for use in commercial aviation pending the necessary approvals. This document provides a summary of the data collected from the Bio-SPK research and technology program, as well as a discussion about the additional data that is being generated to support fuel approval.

2.0 Fuel Development & Testing

2.1 Introduction

A sustainable alternative fuel can be described as one without negative environmental, economic, and social impacts. In addition to having lower lifecycle green house gas (GHG) emissions, sustainable biofuels should not compete with food or fresh water resources or contribute to deforestation, while providing socioeconomic value to local communities where plant stocks are grown. Oil-based energy crops that can meet these sustainability criteria include, but are not limited to jatropha, camelina and algae. Based on the recent results of well-to-wake Life Cycle Assessments (LCA) carried out by Michigan Technological University in conjunction with UOP and Targeted Growth, Bio-SPK made from jatropha and camelina oils using the UOP renewable jet fuel process can achieve a reduction of GHG emissions between 65 and 80 percent relative to petroleum-derived jet fuel. Similar results are projected for algal oil-derived SPK pending commercialization of efficient oil extraction techniques. These research efforts place aviation on a path to reduce environmental impacts relative to petroleum fuels, but the portfolio of ideal sustainable fuels that will support aviation in the future are still in the early stages of being identified.

A chemical processing technique was identified to convert these sustainable bio-derived oils (triglycerides and free fatty acids) to Bio-SPKs. First, the oils were cleaned to remove impurities using standard oil cleaning procedures. The oils were then converted to the shorter chain diesel-range paraffins using UOP’s Renewable Jet Process, which converts the natural oils by removing oxygen molecules from the oil and converting any olefins to paraffins by reaction with hydrogen. The removal of the oxygen atoms raises the heat of combustion of the fuel and the removal of the olefins increases the thermal and oxidative stability of the fuel. A second reaction then isomerizes and cracks the diesel range paraffins, to paraffins with carbon numbers in the jet range. The end product is a Bio-SPK fuel that contains the same types of molecules that are typically found in conventional petroleum based jet fuel. A summary of the fuel production process and well-to-wake LCA is shown in Figure 2.1



- Natural oils contain oxygen, have high molecular weight
- 1st reaction removes oxygen – product is diesel range waxy paraffins
- 2nd reaction “cracks” diesel paraffins to smaller, highly branched molecules
- End product is same as molecules already present in aviation fuel
- End product is independent of starting oil

Figure 2.1 UOP’s Hydrotreated Renewable Jet Process and LCA

2.2 Fischer-Tropsch SPKs (FT-SPKs) and Bio-SPKs

There has been extensive evaluation of SPK produced from a starting material using the Fischer-Tropsch process. A leader in developing and commercializing this technology is Sasol located in Johannesburg, South Africa, and the Sasol FT-SPK jet fuel is approved for use in commercial aviation, but not broadly available. There are many similarities between the processes and the final SPK fuel using a starting material produced by the Fischer-Tropsch process and a process that uses a bio-derived oil. In both processes the final steps is hydroprocessing followed by separation.

2.3 Bio-SPK Fuel Composition and Performance Data

2.3.1 Hydrocarbon Composition of Bio-SPK Fuel Samples

The hydrocarbon composition of the Bio-SPK fuels produced for the test flights were examined by advanced analytical techniques GC-MS, GCxGC-MS and CHN analysis. The result of the analysis was that the Bio-SPK fuels were composed of a combination of normal and iso-paraffins with a small percentage of cyclo-paraffins. The paraffins carbon number and type (iso and n) of the neat Bio-SPKs varies from C9 to C15 which is a typical range found in conventional jet fuel; see Figure 2.2.

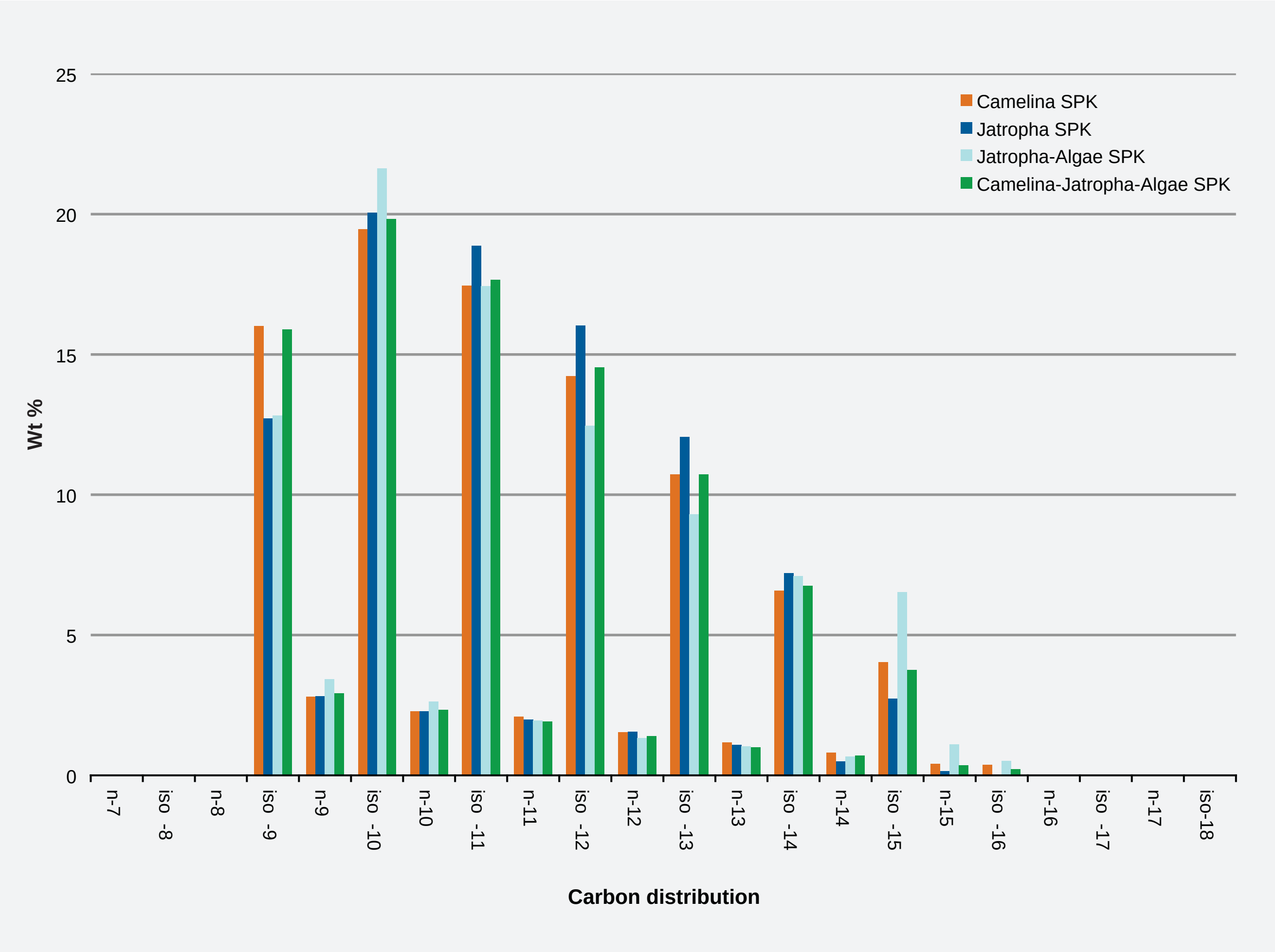


Figure 2.2 Carbon number and type (iso and n) distribution of neat Bio-SPK samples

D5291	**Camelina SPK**	**Jatropha SPK**	**Jatropha-Algae SPK**	**Camelina- Jatropha-Algae SPK**
% C	85.4	85.4	85.7	85
% H	15.1	15.5	15.1	15
% N	<0.10	<0.10	<0.10	<0.10
% C+% H	100.5	100.9	100.8	100
C/H	5.7	5.5	5.7	5.7

Table 2.1 shows the CHN elemental analysis of the Bio-SPK samples by D5291. The samples are pure hydrocarbons with a high level of saturation.

2.3.2 Trace materials

The Bio-SPK samples were further examined for low levels of impurities that could affect the performance of the fuel. The Bio-SPK samples were screened for sulfur, nitrogen and oxygen compounds in addition to 21 metals. The results of the analysis demonstrated that the Bio-SPK jet fuels did not contain any traceable amount of impurities as shown in Table 2.2. It can also be seen that the neat Bio-SPKs are virtually sulfur-free.

2.3.3 Additional Tests

Additional tests have been performed to fully characterize the Bio-SPKs in order to facilitate their approval.

- The dielectric constant of the Bio-SPKs was measured over the temperature range 40°C to +60°C. There is no requirement per ASTM D1655 to measure the dielectric constant of the jet fuel; however, it is very important to the fuel quantity indication system (FQIS).
- The density of each sample and their temperature dependence was measured per ASTM D4052 test method.

			ANZ	**CAL**	**JAL**	
Property		Specification	Jatropha	Jatropha/Algae	Camelina/ Jatropha/Algae	ASTM test
NON-HYDROCARBON COMPOSITION						
Oxygen, wt %			<0.03	<0.03	<0.03	UOP
Nitrogen, ppm		2	<0.4	<0.4	<1	D4629
Water, ppm		75	32.0	34.0	19.0	D6304
Sulfur, ppm		15	<0.01	<0.01	<0.01	D5453
Sulfur, mass %		0.0015	<0.0001	<0.0001	0.0001	D2622
Metals, ppm	Max	0.1 per metal				
Al, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Pd, Pt, Sn, Sr, Ti, V, Zn			<0.1ppm	<0.1ppm	<0.1ppm	
Halogens, ppm	Max	1	<0.1	<0.1	0.2	D7359

Table 2.2 Chemical analysis of neat Bio-SPKs compared to requirements of Table A1-2 from Dxxxx

- A materials compatibility study has been performed with neat Bio-SPKs to check the integrity of aircraft parts in contact with the Bio-SPK fuel; this is important for aspects such as seal swell needed in certain fittings. All samples passed compatibility requirements.
- The boiling point distribution was measured on all Bio-SPK jet fuels and the results show that there is a continuous distribution of hydrocarbons in these samples.

The thermal stability of the Bio-SPKs was checked by JFTOT (ASTM D3241) test method. The “breakpoint” is the highest control temperature at which the fuel meets tube rating and DP specification requirements. All of the neat Bio-SPKs have been tested at 340°C and passed the test as shown in Table 2.3.

				ANZ		**CAL**	**JAL**	
Property		Jet A/Jet A-1	JP-8	**Jatropha**	**Camelina**	**Jatropha/Algae**	**Camelina/Jatropha/Algae**	ASTM Test Method
COMPOSITION								
Acidity, total mg KOH/g	Max	0.10	0.015	0.002	0.002	0.001	0.003	D3242
Aromatics								
1. Aromatics, volume %	Max	25	25	0.0	0.3	0.0		D1319
2. Aromatics, volume%	Max	26.5						D6379
Sulfur, mercaptan, mass %	Max	0.003	0.002	0.0001	<0.0001	<0.0001	<0.0001	D3227
Sulfur, total mass %	Max	0.30	0.30	<0.0001	<0.0001	<0.0001	0.0001	D1266, D2622, D4294 or D5453
VOLATILITY								
Distillation:								
One of the following requirements shall be met:								D2887 or D86
Distillation temperature, °C:								
10 % recovered, temperature (T10)	Max	205	157-205	168	162	164	163	
50 % recovered, temperature (T50)		report	168-229	188	186	187	183	
90 % recovered, temperature (T90)		report	183-262	227	226	233	226.3	
Final boiling point, temperature	Max	300	300	255	251	256	237.7	
Distillation residue, %	Max	1.5	1.5	1.3	1.3	1.2	1.2	
Distillation loss, %	Max	1.5	1.5	0.1	0.2	0.3	0.3	
Final boiling point, temperature (simul)	Max	340						
Flash point, °C	Min	38	38-68	46.5	42.0	41.0	42.0	D56 or D3828
Density at 15°C, kg/L		0.775-0.840	0.775-0.840	0.749	0.753	0.748	0.752	D1298 or D4052
FLUIDITY								
Freezing point, °C	Max	–40 Jet A –47 Jet A-1	-47	-57.0	-63.5	-54.5	-63.5	D5972, D7153, D7154 or D2386
Viscosity –20°C, mm^2/s	Max	8.0	8.0	3.663	3.336	3.510	3.353	D445
COMBUSTION								
Net heat of combustion, MJ/kg	Min	42.8	42.8	44.3	44.0	44.2	44.2	D4529, D3338 or D4809
Hydrogen content, mass %	Min		13.4					
One of the following requirements shall be met:								
(*1*) Smoke point, mm, or	Min	25	25					D1322
(*2*) Smoke point, mm, and	Min	18	19					D1322
Naphthalenes, volume, %	Max	3.0	3.0	<0.01	<0.01	<0.01	<0.01	D1840
CORROSION								
Copper strip, 2 h at 100°C	Max	No. 1	No. 1					D130
THERMAL STABILITY								
JFTOT (2.5 h at control temperature)								
Temperature, °C	Min	260		340	340	340	300	D3241
Filter pressure drop, mm Hg	Max	25	25					
Tube deposits less than		3	3	1	<1	1	1	
CONTAMINANTS								
Existent gum, mg/100 mL	Max	7	7		<1	<1	<1	D381, IP 540

Table 2.3 Properties summary of neat Bio-SPKs against existing jet fuel specifications

2.4 Bio-SPK Flight Test Program Samples

After an initial screening of the Bio-SPKs, a decision was made to conduct a series of flight tests using a 50 percent by volume blend of Bio-SPK and petroleum-based jet fuel. As part of the test program, laboratory fuel property testing took place at multiple locations including Boeing, Honeywell/UOP, Air Force Research Lab (AFRL), several independent outside laboratories and at participating engine companies. The three Bio-SPK fuels used for the flights and the CFM engine ground test effectively met all ASTM D1655 performance specifications at a 50 percent blend with petroleum-based jet fuel (Table 2.5). Additional property and performance tests were performed to support approval to use the experimental fuels including materials compatibility testing.

A summary of the test flights and the feedstocks that were used to produce the fuel are shown in Table 2.4 below: In all of the Bio-SPK test flights only one engine was fed with the Bio-SPK jet fuel blend.

Airline	**Air New Zealand**	**Continental Airlines**	**Japan Airlines**
Aircraft	Boeing 747-400	Boeing 737-800	Boeing 747-300
Engine	Rolls-Royce RB211-524G	CFM International CFM56-7B	Pratt & Whitney JT9D-7R4G2
Plant Feedstock	50% jatropha	47.5% jatropha, 2.5% algae	42% camelina, 8% jatropha/algae
Fuel Provider for Test Flight	UOP	UOP	Nikki Universal/UOP
Flight date	Dec 30, 2008	Jan 7, 2009	Jan 30, 2009
Engine Tests/Ground Run Results	Comparison of fuel flow with expected heat of combustion	Engine Operability & Emissions Tests for various blend percentages	Engine Operability & Emissions on Neste Oil-provided paraffins for ground engine test only.
Flight Test Profile	Climb to FL 350, Mach 0.84 accels & decels, engine windmill restarts, starter-assisted engine relights, simulated missed approach, suction feed test	Climb to FL390, Mach 0.78, accels & decels, engine windmill restarts, starter-assisted engine relights, simulated missed approach, suction feed test	Climb to FL390, Mach 0.80, accels & decels, engine windmill restart, suction feed test. Was the only hydro-mechanical engine used for this series of flight tests.

Table 2.4 Bio-SPK Test Flight Summary

2.5 Properties summary for the Bio-SPK jet fuel blends

Property		**Jet A / Jet A-1**	**ANZ**	**CAL**	**JAL**	**ASTM Test Method**
Mixture of Jet A or Jet A-1 // SPK is in			50	50	50	
Volume % Blended with			Jet A-1	Jet A	Jet A	
		Part 1: Basic Requirements				
COMPOSITION						
Acidity, total mg KOH/g	Max	0.10	0.002	0.001	0.002	D3242
Aromatics: one of the following requirements shall be met						
1. Aromatics, volume %	Max	25	8.8	9.2	8.9	D1319
2. Aromatics, volume %	Max	26.5	N/A	N/A	N/A	D6379
Sulfur, mercaptan, ^{C} mass %	Max	0.003	0.0004	<0.0001	0.0003	D3227
Sulfur, total mass %	Max	0.30	<0.015	<0.0001	0.0403	D1266, D2622, D4294 or D5453
VOLATILITY						
Distillation:						
Distillation temperature, °C:						D2887 or D86
10 % recovered, temperature (T10)	Max	205	170.4	170.5	171.0	
50 % recovered, temperature (T50)		report	190.3	194.0	200.5	
90 % recovered, temperature (T90)		report	226.9	228.0	240.0	
Final boiling point, temperature	Max	300	246.8	248.5	258.0	
Distillation residue, %	Max	1.5	1.2	1.2	1.2	
Distillation loss, %	Max	1.5	0.4	0.2	0.2	
Flash point, °C	Min	38	45.0	45.0	44.5	D56 or D3828
Density at 15°C, kg/m^3		775 to 840	779	780	789	D1298 or D4052
FLUIDITY						
Freezing point, °C	Max	–40 Jet A –47 Jet A-1	-62.5	-61.0	-55.5	D5972, D7153, D7154 or D2386
Viscosity –20°C, mm^2/s	Max	8.0	3.606	3.817	4.305	D445
COMBUSTION						
Net heat of combustion, MJ/kg	Min	42.8	43.6	43.7	43.5	D4529, D3338 or D4809
One of the following requirements shall be met:						
(*1*) Smoke point, mm, or	Min	25	33			D1322
(*2*) Smoke point, mm, and	Min	18		27.7	28.6	D1322
Naphthalenes, volume, %	Max	3.0	N/A	0.2	1.2	D1840
CORROSION						
Copper strip, 2 h at 100°C	Max	No. 1	1A	1A	1A	D130
THERMAL STABILITY						
JFTOT (2.5 h at control temperature)						
Temperature, °C	Min	260	300	300	300	D3241
Filter pressure drop, mm Hg	Max	25	3.0	0.0	0.2	
Tube deposits less than		3	1.0	1.0	1.0	
		No Peacock or Abnormal Color Deposits				
CONTAMINANTS						
Existent gum, mg/100 mL	Max	7	1.0	<1	<1	D381, IP 540
Microseparometer, Rating						D3948
Without electrical conductivity additive	Min	85				
With electrical conductivity additive	Min	70				
ADDITIVES		See 6.3				
Electrical conductivity, pS/m			123.0	<1	<1	D2624
		Part 2: Extended Requirements				
COMPOSITION						
Aromatics: one of the following requirements shall be met						
1. Aromatics, volume %	Min	8	8.8	9.2	8.9	D1319
2. Aromatics, volume %	Min	8.4	N/A	N/A	N/A	D6379
Distillation:						D2887 or D86
T50-T10, °C:	Min	15	19.9	23.5	29.5	
T90-T10, °C:	Min	40	56.5	57.5	69	
Lubricity, mm	Max	0.85	0.64	0.65	0.66	D5001

Table 2.5 Comparison with data from Table 1 from Dxxxx, Detailed Requirements of Aviation Turbine Fuels Containing Synthesized Hydrocarbons

3.0 Engine Operability, Emissions, & Flight Test Program

Engine tests occurred at General Electric's Ohio facility on a fully instrumented CFM56-7B development engine. Performance and operability testing in addition to emission evaluation were performed comparing a baseline Jet A with 50 percent and 25 percent Bio-SPK fuel blends, respectively. Performance testing measured Specific Fuel Consumption (SFC) at several power settings from ground idle to take-off. Operability testing measured start times, lean-blow out margin, acceleration and deceleration times. The emissions testing measured the currently regulated emissions species; Nitrogen Oxides (NOx), Carbon Monoxide (CO), hydrocarbons (HC), and smoke number. The emissions of the Bio-SPK fuel blends all measured within the normal expected variation of jet fuel.

A series of engine ground runs were conducted on an Air New Zealand Boeing 747-400 aircraft equipped with Rolls Royce RB 211-524G engines prior to the test flight including a switch of fuel at various progressions of Engine Pressure Ratio (EPR) settings. The engine showed no change in behavior from an operational perspective. The Digital Flight Data Recorder (DFDR) data from the EPR of 1.4 is shown in Figure 3.1. The 1.07 percent lower fuel flow that was observed on the engine run of the Bio-SPK jet fuel blend is consistent with the 1.08 percent higher energy density per unit mass of the Bio-SPK fuel blend, which was determined experimentally.

For all flights, a detailed analysis was made for the following parameters from each engine, as applicable, for parameters such as altitude, airspeed (VCAS), engine pressure ratio, N1%, N2%, N3%, EGT (C°), P3, fuel flow, and throttle angle. Also, borescope analyses were conducted before and after each test to detect any potential engine deterioration.

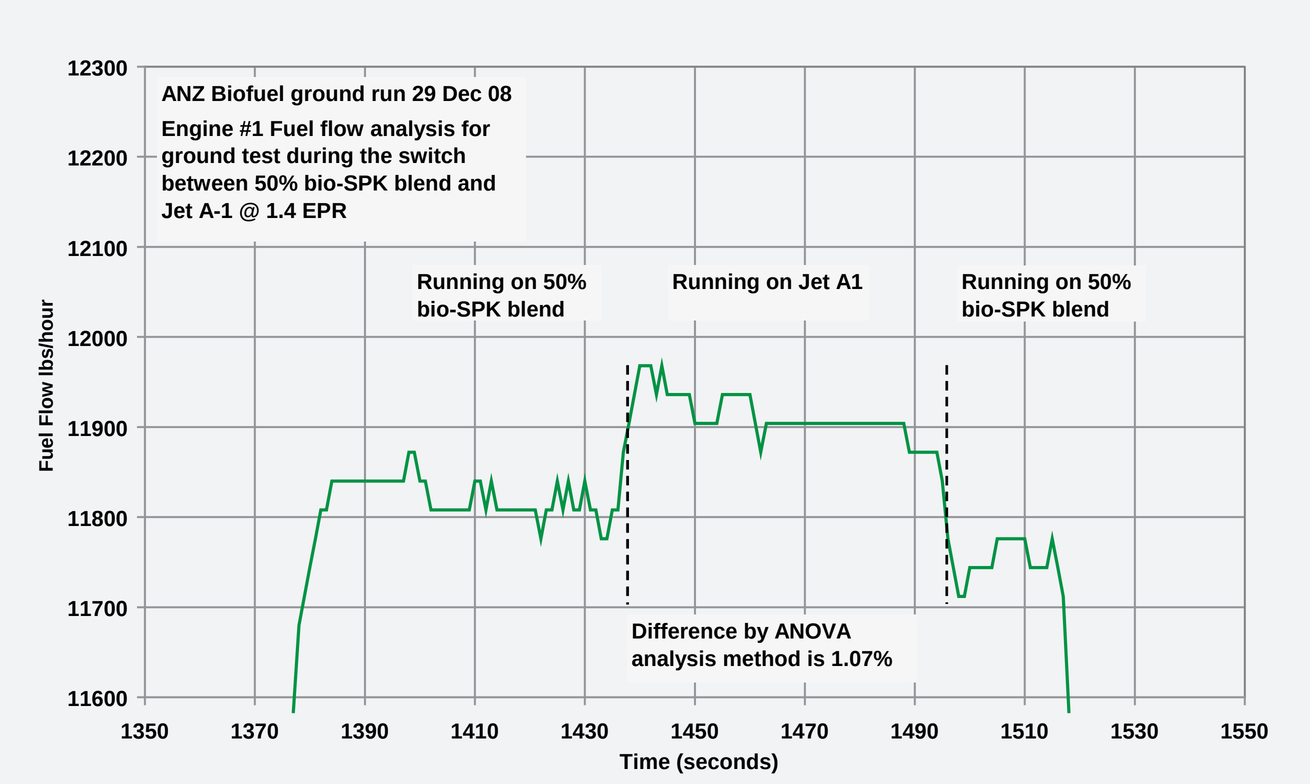


Figure 3.1 Engine ground run data is shown from a Rolls Royce RB211-524G engine taken at Auckland on Dec. 30 2008. The data shows a reduction in fuel flow, due to the higher heat of combustion of the 50 percent Bio-SPK fuel blend.

4.0 Performance Summary

Findings from this research and test program, as well additional testing that is currently in progress, will be used to support sustainable biofuel development and approval for use in aviation. The program engaged fuel suppliers, engine companies, and the airlines as a team effort to address industry concerns about CO_2 emissions, fuel availability, and cost. A commercial-ready Bio-SPK fuel production process was scaled upward from the initial DARPA program research phase, to demonstrate its viability to produce a replacement jet fuel blend and fuel property that takes airframe compatibility and engine operability & emissions tests into consideration. The Bio-SPK fuel blends used in the test flights have all either met or exceeded the performance specifications for jet fuel. For example, the Bio-SPK fuel blends demonstrated higher energy density per unit mass than typical jet fuel, enabling airplanes to travel farther using less fuel. For all of the test flights, the blended biofuel displayed no adverse effects on any of the aircraft systems.

5.0 Next Steps – Fuel Approval

The Bio-SPK flight test and research program generated valuable data to support approval of Bio-SPK at up to a 50 percent blend ratio. Boeing, in cooperation with Honeywell/UOP and the US Air Force Research Laboratory, is currently preparing a comprehensive research report to be submitted to the ASTM International Aviation Fuel Committee, which will follow the guideline outlined in the revised ASTM D4054 document entitled “Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives.” Reporting for other fuel specifications will be made, as required. The majority of fit-for-purpose and auxiliary power unit engine and combustion rig tests have been completed in addition to emission evaluation. We are currently gathering data from these tests for inclusion in the research report along with data generated from the Bio-SPK flight test program. Preliminary examination of the results of those tests is extremely encouraging.

Glossary

Algae

Algae, which can be grown in brackish or polluted water, unsuitable for drinking or agriculture, can be harvested for oil which can be processed into biofuel. This isn't large scale yet, but could potentially provide a significant proportion of aviation's fuel needs.

ASTM International

Originally known as the American Society for Testing and Materials, this international standards organization develops and publishes voluntary consensus technical standards for a wide range of materials, services, systems and products.

Air Force Research Lab (AFRL)

Headquartered at Wright-Patterson Air Force Base, Ohio, AFRL is a full-spectrum laboratory, responsible for planning and executing the US Air Force's science and technology program.

Biofuel

Fuel produced from renewable resources. Aviation is focused on advanced generation biofuels derived from sustainable biomass that do not impact the food supply chain or fresh water resources or contribute to deforestation.

Biomass

Any organic matter that can be converted into fuel.

Bio-SPK

A synthetic paraffinic kerosene that was produced from a bio-derived oil source

Neat Bio-SPK

100 percent Bio-SPK

DARPA

Defense Advanced Research Projects Agency

Fischer-Tropsch Process

A chemical reaction process that uses a catalyst to react carbon monoxide and hydrogen to make hydrocarbons.

Fischer-Tropsch SPK

A synthetic paraffinic kerosene that was produced from a starting material using the Fischer-Tropsch process

Free Fatty Acids

A carboxylic acid with an aliphatic chain that is either unsaturated or saturated in a mixture of triglyceride oil

Jet A/Jet A-1

Jet A is the recognized US specification for jet fuel, Jet A-1 is the internationally recognized specification for jet fuel outside of North America. Both specifications have similar criteria for density, heating values (i.e. energy contents), but Jet-A1 has a slightly lower freeze point than Jet-A

Hydroprocessing

Hydroprocessing is process technology widely used in the refining industry for the production of clean, transportation fuels. The technology utilizes catalysts in the presence of hydrogen to convert a variety of feedstocks, including biologically derived materials, into high-quality fuels.

Iso-Paraffins

Branched chain paraffins

Jatropha

A plant that produces seeds which are an efficient source of oil for conversion into Bio-SPK. It can be grown in arid regions on land that would not support food agriculture.

Kerosene

The common name for petroleum-derived jet fuel such as Jet A-1. In addition to its use in aviation, kerosene can be used for a variety of other purposes.

n-parafffins

Straight chain paraffins

Synthetic Paraffinic Kerosene (SPK)

Aviation fuel that contains predominantly paraffins produced from non-petroleum feedstocks

UOP

UOP LLC, a Honeywell company is a leading international supplier and licensor of process technology, catalyst, adsorbents, equipment and consulting services to petroleum refining, petrochemical, and gas processing industries. UOP technology for the production of clean, high quality fuels and petrochemicals is used today in almost every refinery around the world.

UOP's Renewable Jet Process

Proprietary chemical processing techniques that can convert sustainable bio-derived oils (triglycerides and free fatty acids) to Bio-SPKs.

CHN

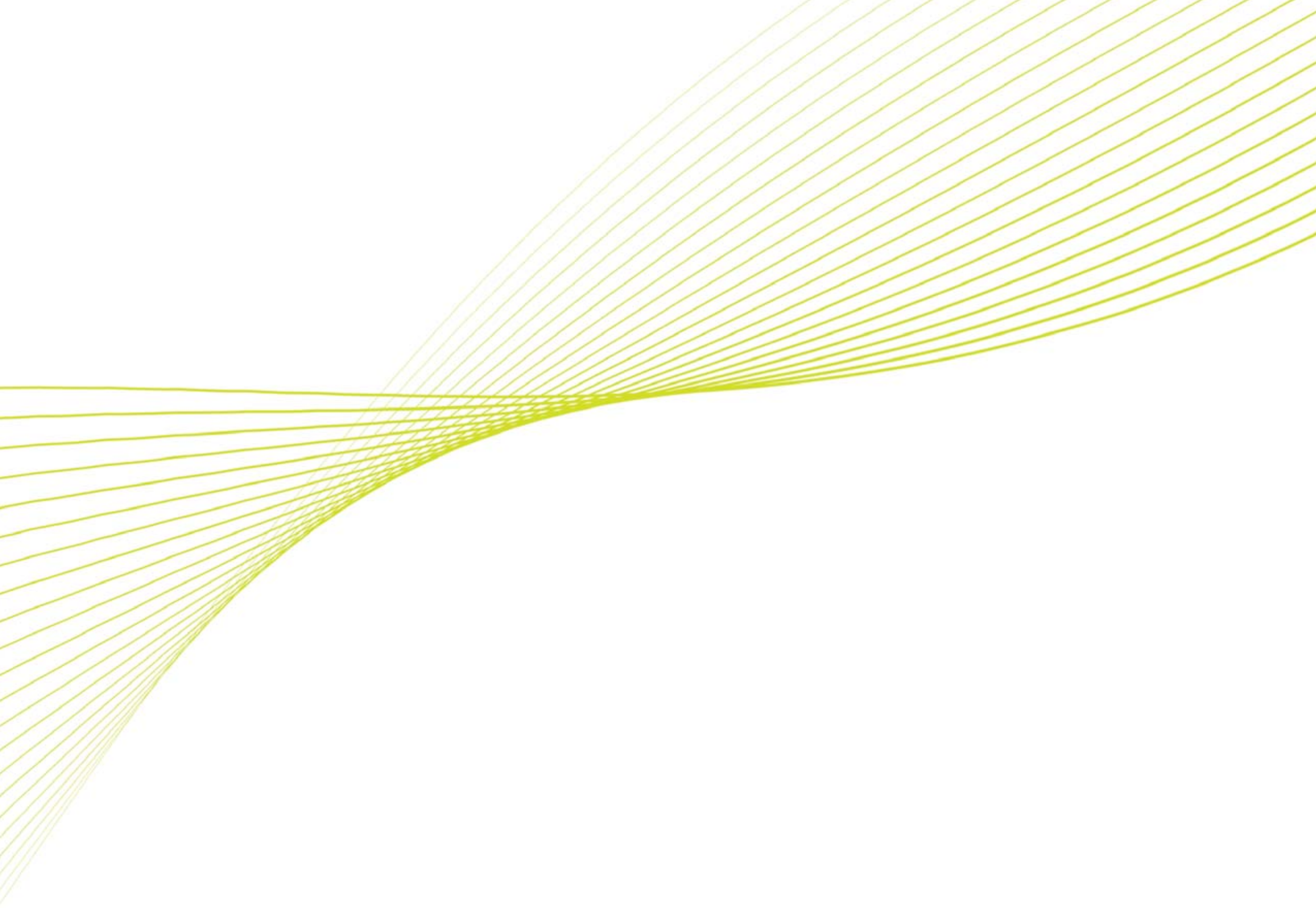
Carbon, Hydrogen, Nitrogen

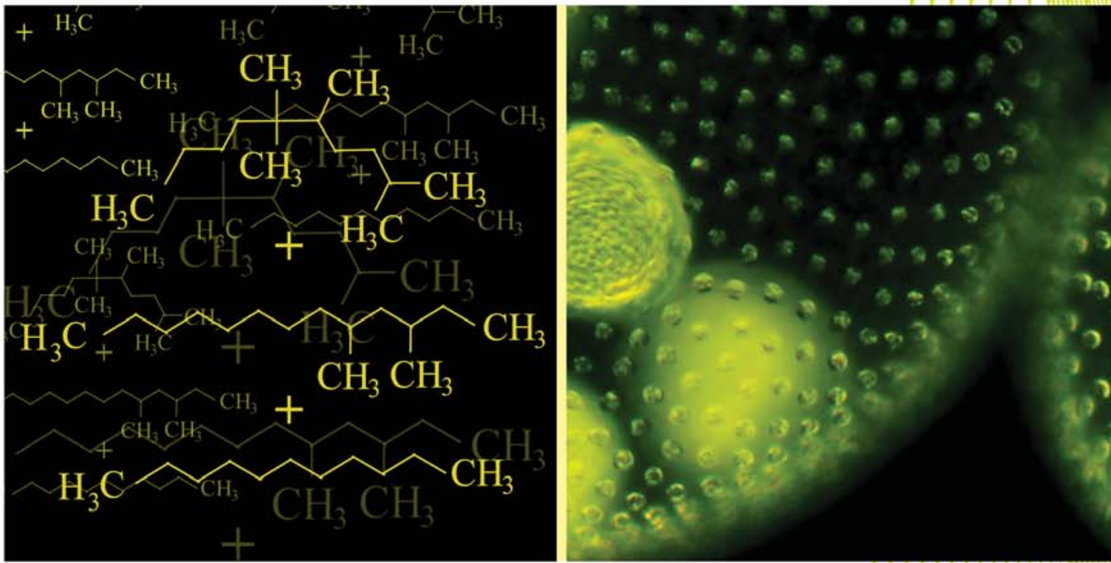
GC-MS

Gas Chromatography-Mass Spectrometry. GC-MS is an analytical technique that combines gas chromatography with mass spectrometry to identify chemical compounds

GCxGC-MS

A gas chromatography method that utilizes two gas chromatography separation steps followed by analysis by mass spectrometry

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