CONFERENCE ON AVIATION AND ALTERNATIVE FUELS

Rio de Janeiro, Brazil, 16 to 18 November 2009

Agenda Item 2: Technological feasibility and economic reasonableness

FLIGHT TESTS AND ASSOCIATED RESULTS

(Presented by the International Coordinating Council
of Aerospace Industries Associations)

SUMMARY

Several flights, which covered a wide range of available aircraft-engine combinations, as well as different sources of alternative fuels were successfully performed in 2008 and 2009. They played an important part in the work that lead to publication on 28 September 2009 of ASTM D7566, entitled "Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons". This paper gives an overview of these flights as well as some associated results.

1. INTRODUCTION

1.1 Over the past few years, sustainable alternative fuels have started to be considered as an opportunity to explore, in order to contribute to the reduction of the environmental impact of aviation. Prior to this time, the only approved alternative fuel was a blend of conventional kerosene and a maximum of 50% kerosene produced from coal (CTL).

1.2 During this time CTL (from one supplier) has been approved to 100% through a full suite of rig, engine, and aircraft tests.

1.3 Subsequently, test flights could be envisaged to demonstrate initially the capability of aircraft to fly and engines to run on a drop-in fuel different than conventional kerosene. Several flights, which covered a wide range of available aircraft-engine combinations, as well as different sources of alternative fuels were successfully performed in 2008 and 2009.

2. RESULTS

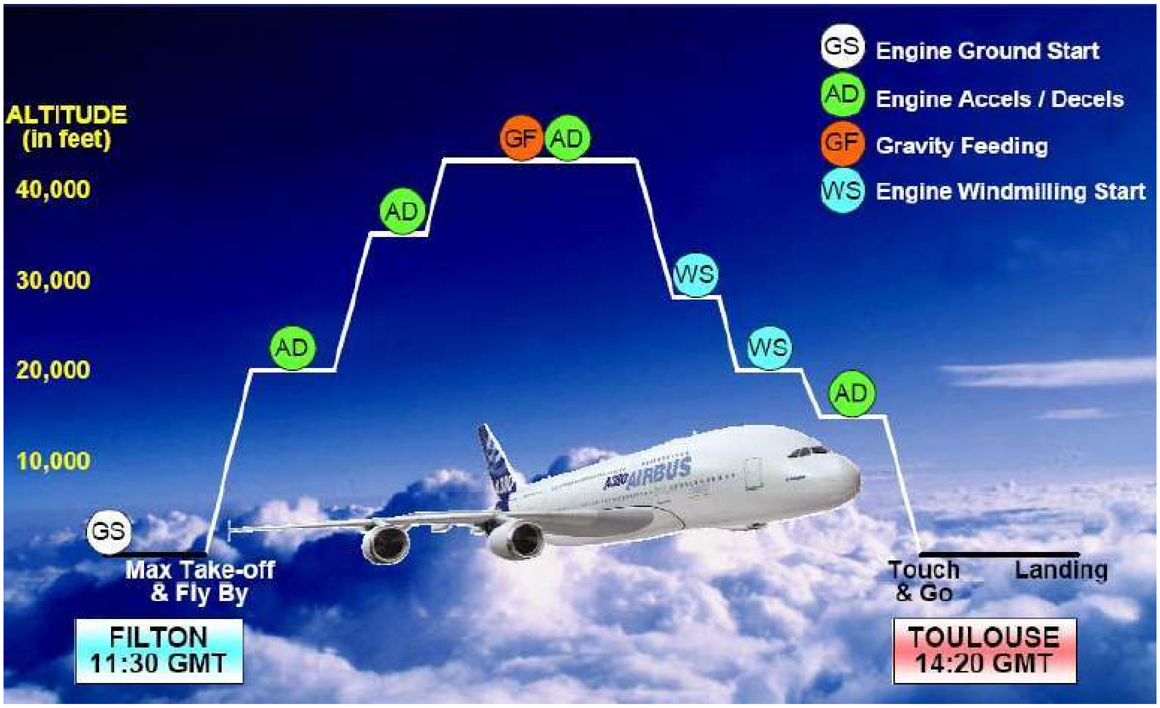
2.1 The series of flights for three commercial aircraft using the Bio-SPK blends occurred in late 2008 and early 2009 with Air New Zealand, Continental Airlines, and Japan Airlines. For all flights, a detailed analysis was carried out for the following parameters from each engine, as applicable: altitude, airspeed (VCAS), engine pressure ratio (EPR), N1%, N2%, N3%, EGT, P3, fuel flow, and throttle angle. Also, boroscope analyses were conducted before and after each test to detect any potential engine deterioration.

2.2 Airbus A380 Flight Test with GTL

2.2.1 On the 1st of February 2008, an Airbus A380 aircraft powered by Rolls-Royce Trent 900 engines successfully completed the world’s first ever flight by a commercial aircraft using a synthetic liquid fuel processed from gas (Gas to Liquids - GTL). The fuel was provided by Shell International Petroleum and enabled a three-hour test flight from Filton, UK to Toulouse, France. During the flight, engine number one was fed with a blend of GTL and Jet A-1 kerosene whilst the remaining three engines were fed with conventional Jet A-1 kerosene.

2.2.2 Analysis of the data recorded whilst the aircraft was fuelled and during the flight, and from materials testing, has shown that the use of the GTL blend had no adverse effect on the engine, aircraft systems or materials and it behaved like a conventional Jet A-1 kerosene. The test results obtained from the testing confirm predictions that GTL is a good candidate as a suitable alternative fuel for commercial aviation.

2.2.3 During this flight, the following phases and tests were performed:



- Engine 3 + 4 starts from APU bleed;
- Engine 1 + 2 starts from APU bleed;
- Max take off and climb up to FL200;
- FL200/300kts, engine 1 transients between idle and MCL;
- Climb up to FL350;
- FL350/MN0.86, engine 1 transients between idle and MCL;
- Climb up to FL430 and engine 1 fuel boost pump switched OFF;
- FL430/MN0.85, engine 1 transients between idle and MCL in gravity feed, 37 minutes after passing FL300 (de-aerated fuel);
- Engine 1 fuel boost pump switched ON;
- Engine 1 shutdown at FL425/MN0.85 and descent down to FL280;
- FL280/337kts, engine 1 wind milling relight;
- Engine 1 shutdown;
- FL200/252kts, engine 1 wind milling relight;
- FL150/340kts, engine 1 bodies between idle and MCL;

- Approach;
- Touch and go manoeuvre with TOGA power requested on four engines;
- Aircraft Feed tank 1 was empty and engine 1 was fed from feed tank 2+3; and
- Landing with max reverse applied (all engines fed with JetA1).

2.2.4 **Results**

2.2.4.1 Engine transients:

- During take off performed at max power; engine 1 showed similar behaviour with the other three engines;
- During transient manoeuvres preformed in normal feed and gravity feed with de-aerated fuel, engine 1 showed correct behaviour: no stall or engine misbehaviour was observed.

2.2.4.2 Engine starts

- Engine 1 starter assisted ground start with air from APU bleed was performed without malfunction in 60s. This start time is similar to the start time of the other three engines fed with Jet A1;
- Two engine 1 wind milling air starts were performed without malfunction, start time are similar to those observed during the certification campaign on T900 engines with Jet A1 fuel.

2.3 Virgin Atlantic Flight Test

2.3.1 In February 2008, a Virgin Atlantic 747-400, powered by General Electric GE CF6 engines flew from London to Amsterdam using a 20% mix of Synthetic Paraffinic Kerosene (SPK) biofuel (Bio-SPK) from coconut and babassu oils in one of its four engines. The Boeing 747-400 took off from Heathrow Airport at 11.34 and landed at Amsterdam Schiphol Airport at 12.14.

2.3.2 In preparation for the flight, Boeing, GE Aviation and Imperium conducted extensive laboratory and static-engine testing on the ground to evaluate the energy and performance properties of the biofuel used in the flight. The Virgin Atlantic flight is the first step in a broader industry-wide initiative to commercialise alternative fuel sources for aviation and Virgin Atlantic will be sharing the results with those also seeking to cut their carbon emissions in the rest of the industry.

2.4 **Air New Zealand Flight Test**

2.4.1 An ANZ 747-400 equipped with Rolls-Royce RB211-524G2-T engines was used to test the 50% Bio-SPK blend in an engine ground run on December 29, 2008 and an experimental flight from Auckland, New Zealand, which occurred on December 30, 2008. The biofuel was kept separate from the other aircraft systems and only fed to engine #1, in a direct tank-to-engine configuration. Onboard observers monitored the performance of engine #1 during all stages of the test flight. Evaluation of the DFDR data was conducted to gain a better understanding of the fuel performance. The flight lasted approximately 2 hours, and consisted of a climb to FL350, and thereafter-included engine windmill restarts at FL260/300kts as well as using starter-assist at FL180/220kts. Acceleration and deceleration checks were carried out at FL350, Mach 0.84. A simulated approach-and-go-around was conducted at 10,000 ft.

2.4.2 **Flight Crew Observations**

2.4.2.1 Based on the pilots' comments, the following observations were made:

- Start and light-off – Engine #4 was started in accordance with normal procedures. Engine #1 was then started using normal procedures followed by engines #2 and #3. Engine #1 start was as expected with no noticeable difference in starting characteristics. Idle checks were carried out on engine #1 and normal operating conditions were observed;

- Take-off – A full power (for the day's atmospheric conditions) takeoff was carried out. Power was advanced to approx 1.1 EPR while aircraft brakes were held on. Brakes were released and the engines advanced to full rated thrust. Engine #1 spooled up as other engines. Takeoff roll was approximately 1800 feet with Vr at 121kts • Climb – During climb at approximately FL200 the #1 fuel tank boost pumps were switched OFF to verify suction feed to engine #1. Operation was normal. At approximately FL250 the #1 fuel tank boost pumps were switched back ON. Anti-Ice was used above FL260 as conditions required;

- Rapid accels/decels – After establishing stable conditions at FL350 and recording stable cruise data the aircraft was configured for accel/decel tests. Engine #1 throttle was quickly reduced to idle and the engine responded normally. The engine was allowed to stabilize, then the throttle was quickly advanced to maximum EPR. The engine responded smoothly and reached the commanded EPR in a normal time. There was no sign of instability or hang up;

- Relights – Aircraft descended to FL180/ 260kts where two 'Starter assisted' relights were carried out. Both restarts were normal;

- Take Off Go Around – The aircraft descended and a landing configuration was established for a simulated approach to a way point 'runway' at 8000ft. From this point a missed approach and go around was carried out. All engine operations were normal;

- Landing & Reverse Thrust – A normal approach and landing were then carried out with 'Full' Reverse thrust used on all 4 engines. Normal operation was observed;

- Taxi & shutdown – Aircraft was taxied to the shut down point where all 4 engines were shut down. Engine #1 shutdown was normal. After allowing time for EGT to drop, engine #1 was restarted and allowed to stabilize. Start was normal. Engine #1 was then shutdown normally.

2.4.3 **Post Flight Data Analysis**

2.4.3.1 The data was analyzed for the engine ground run and the test flight. No issues arose during the test flight with the engine #1 running on 50% Bio-SPK blend. The aircraft and engine performance were as expected and the fuel blend gave similar results in operation to those found during ground-based testing. Figure 11 shows the flight profile for this flight, consisting of approximately 2 hours and cruise at FL350. In general, the data is of good quality, and the engines are very well matched on main parameters. There was an engine change just prior to this biofuel test, so no reference flight data is available with Jet A-1 on test engine. There were no obvious signs of Bio- SPK blend impacting engine operation. Post flight hardware checks included the inspection of 24 fuel nozzles (Parker), fuel management unit and fuel pump, and the low pressure fuel filter. There were no apparent effects from use of the Bio-SPK blend.

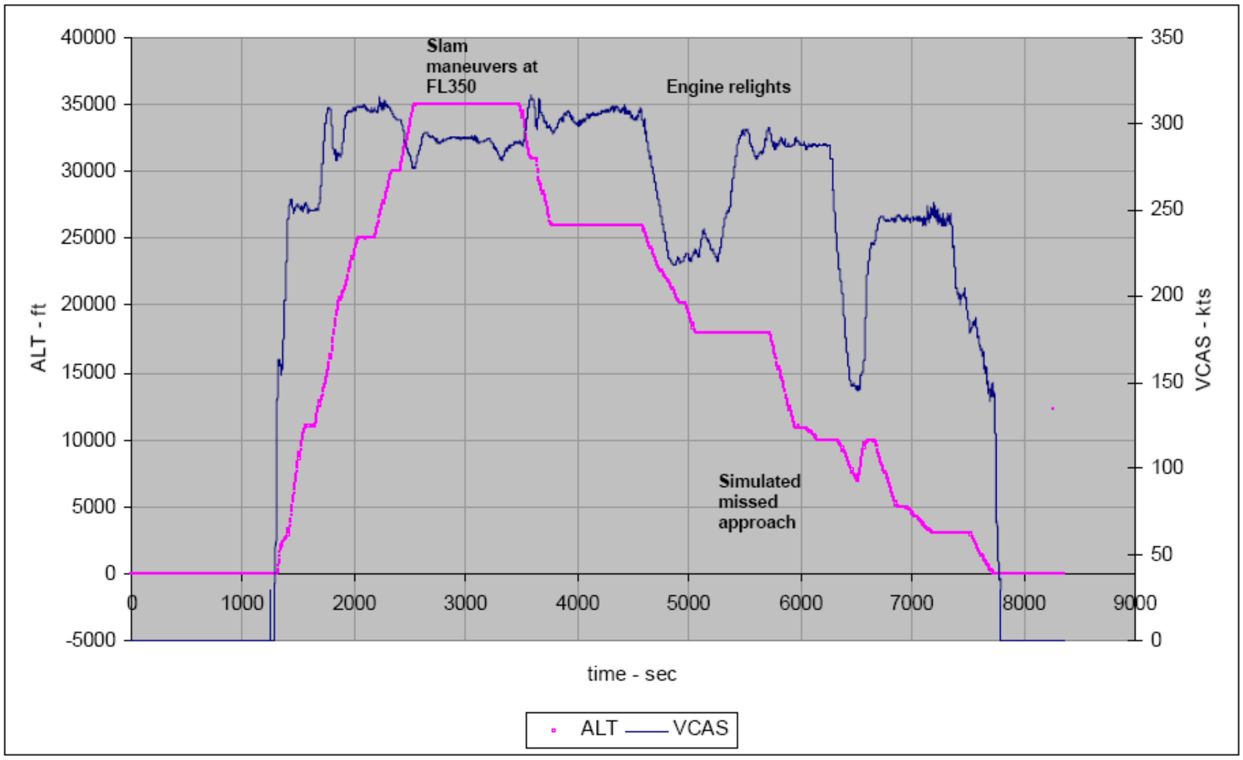


Figure 1 - Air New Zealand 747-400 Flight test profile and events during the flight test.

2.5 Continental Airlines Flight Test

2.5.1 A 737-800 equipped with CFM56-7B engines was used to test 50% jatropha/algae based Bio-SPK blend in an engine ground run on January 6, 2009, and an experimental flight from Houston, Texas on January 7, 2009. The flight lasted approximately 2 hours, and consisted of a climb to FL 390, engine accelerations and decelerations at FL390, Mach 0.78, a windmill engine restart at FL250/280kts, a starter assisted restart at FL250/230kts, and a simulated go-around manoeuvre at 10,000 ft.

2.5.2 **Prior to the test flight**

- No physical modifications were made to the aircraft or systems, no special instrumentation was installed and boroscope inspections were performed on engine #2.
- Engine #1 and the APU were supplied with Jet A from fuel tank #1. The aircraft fuel system was configured in a tank-to-engine configuration for starting, taxiing and flight to ensure that only the engine #2 received biofuel from the tank #2.
- The following #2 engine ground tests on biofuel were performed: engine start time, power assurance & accels.

2.5.3 **Flight Crew Observations**

2.5.3.1 Onboard observers monitored the performance of the engine #2 during all stages of the test flight. The aircraft and engine performance were unaffected by the biofuel and performance differences were un-distinguishable from the engine #1 running on Jet A. Engine #2 performance matched its characteristics when run prior on Jet A.

2.5.3.2 The pilots performed the following flight procedures:

- Engine start and taxi
- Takeoff
- Climb to cruise altitude and stabilize engine readings
- Rapid throttle excursions
- In flight restarts
- Descent with simulated go-around
- Final descent and landing

2.5.3.3 The mission profile is shown in Figure 2. The aircraft and engine performance were as expected and the fuel blend gave similar results in operation to those found during ground based testing.

2.5.4 **Post Flight Data Analysis**

2.5.4.1 The QAR data was analyzed for the engine ground run and the test flight. A manual rolling thrust set was used and both engines achieved the target 10% derate takeoff thrust 26 seconds into the takeoff roll. Slight differences in throttle angle were evident between the two engines due to the manual thrust set, which resulted in slightly different N1 speeds during the take-off acceleration. The acceleration rate of engine #2 running on biofuel matched the acceleration rate of the engine running on Jet A.

2.5.4.2 Both engines behaved similar with respect to EGT and the peak EGT achieved by both engines were identical. To allow for the most representative comparison of the Bio-SPK blend and Jet A consumption, an analysis was performed using two flight segments each (climb and cruise) from the previous revenue service flight and the biofuels flight. The flight segments were chosen where the flight parameters (i.e., altitude, Mach number, total air temperature, fan speed) were stable in order to eliminate variation due to throttle movements. The engine quality/health difference (between engines #1 and #2) was first established from the previous flight with the typical Jet A fuel. The flight test fuel flow rate is acquired using the engines mass flow meter. The precision of this fuel flow measurement is approximately +/- 0.5.

2.5.4.3 Several climb segments were used to compare the previous revenue service flight (with Jet A) to the biofuels test flight. The previous flight showed an improved fuel flow for engine #2 versus engine #1 of –0.6%. This generalizes the difference in fuel burn performance of engine #2 relative to engine #1 for the same fuel. During the biofuel test of engine #2, a fuel flow improvement of –1.8% was observed. The engine performance difference from the previous flight (-0.6%) was then subtracted from the biofuels result (-1.8%) to compute –1.2% fuel flow improvement from the biofuel only. Similar analysis was also conducted for the cruise segment of the biofuels flight. The observed –2.1% improvement was adjusted for the –0.6% performance difference as previously discussed. The net improvement due to the biofuel is seen to be –1.5%. The analysis is shown graphically in Figure 3. Both the climb and cruise segments match the expected fuel flow reduction of -1.1% as shown in Table 3 fairly well.

2.5.4.4 As part of verifying the operability of the Bio-SPK blend, rapid throttle excursions were performed during the test flight. Engine #2, running on the Bio-SPK blend, had its power reduced from a cruise setting to idle. Once the engine had stabilized at idle, a snap acceleration to maximum continuous thrust was commanded. Engine #2, running the Bio-SPK blend, responded as expected with no thrust delay or other anomaly noted in the data; this is consistent with crew reports after the flight. Two stabilized engine restarts were performed during the flight test, a windmill restart and a starter assisted restart. Engine #2, running on the Bio-SPK blend, responded as expected and was within experience for engine windmill and starter assisted restarts. After extensive precautionary maintenance, inspections, and analyses, including defueling, change of fuel filter, and boroscope examination, the aircraft returned to service the next day. The engine and airframe have been monitored, and nothing abnormal has occurred.

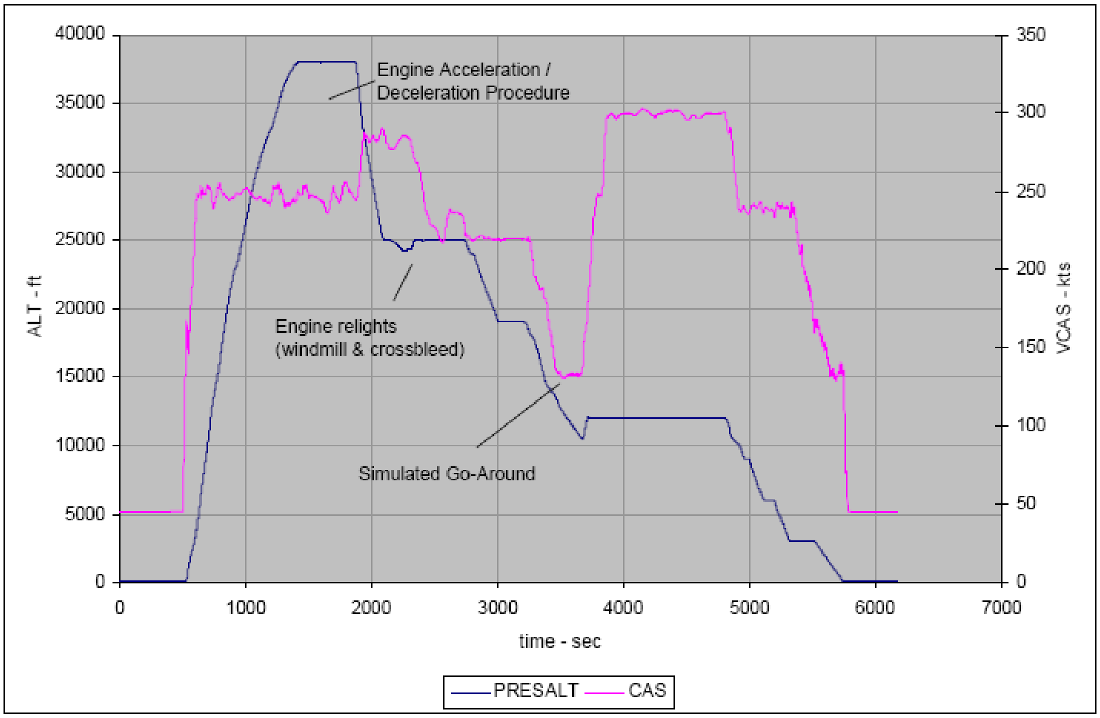


Figure 2. Continental Airlines 737-800 flight test profile on January 7, 2009

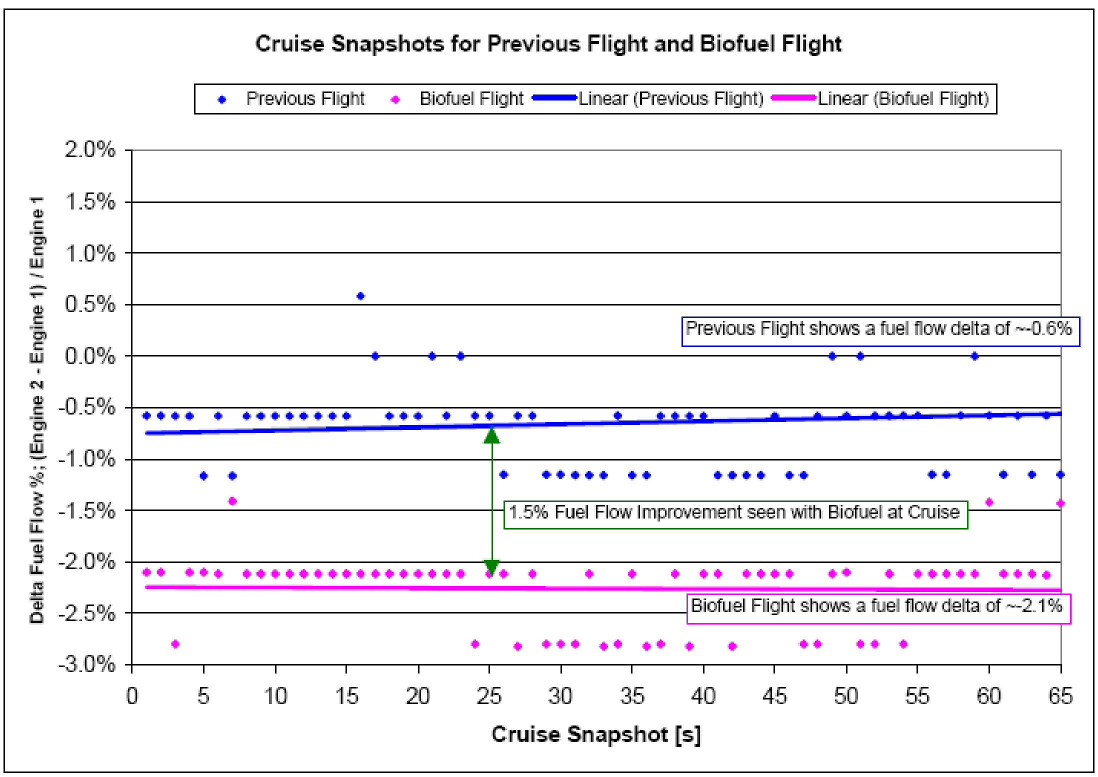
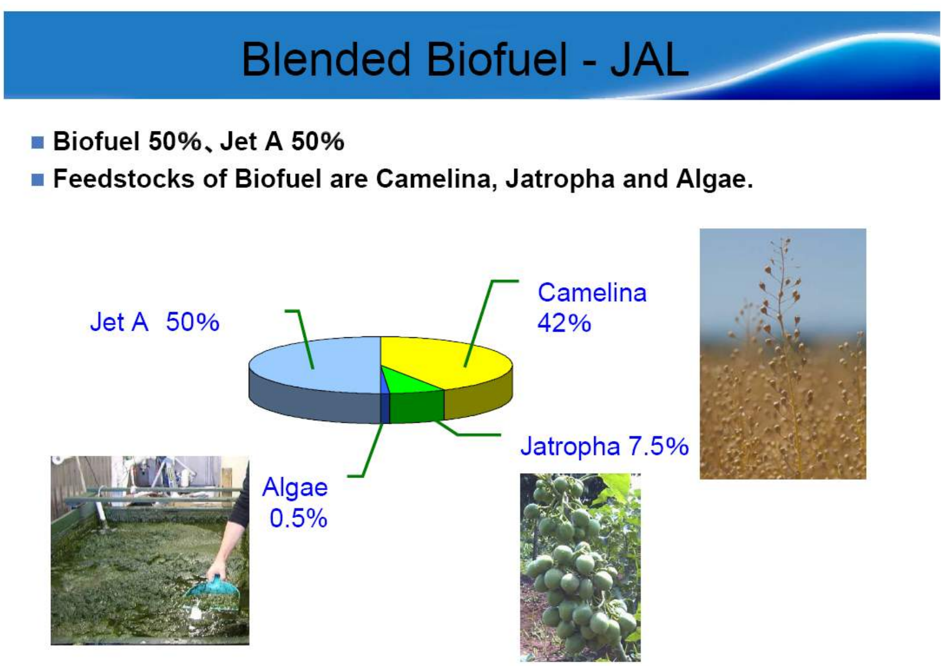
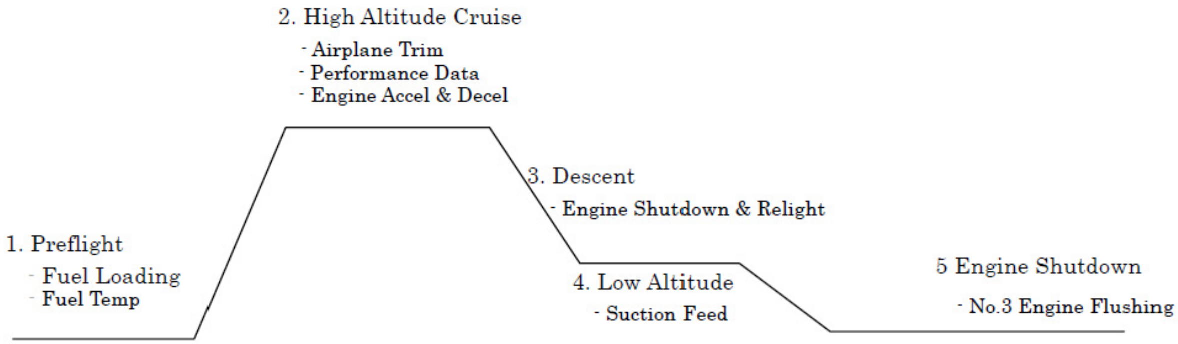


Figure 3. Cruise snapshots for previous Continental Airlines 737-800 flight and biofuel flight

2.6 Japan Airlines Flight Test

2.6.1 The JAL 747-300 flight test, equipped with Pratt & Whitney JT9D engines was used to test a 50% camelina/jatropha/algae Bio-SPK blend in a ground run on January 29, 2009, and a flight in Tokyo, Japan on January 30, 2009. The Bio-SPK blend was kept separate from the other aircraft systems and only fed to engine #3, in a direct tank-to-engine configuration. The flight lasted approximately 2 hours, and consisted of a climb to FL 390, engine accelerations and decelerations at FL350, Mach 0.80, as well as at FL200, 280kts, and an engine windmill restart at FL250, 300kts.





2.6.2 **Flight Crew Observations**

Onboard observers monitored the performance of the engine #3 during all stages of the test flight. The flight crew observed that aircraft and engine performance was unaffected by the blend and performance differences were indistinguishable from the engine #2 running on Jet A-1. The engine #3 performance qualitatively matched its characteristics when run prior on Jet A-1. This was possible, as the same flight crew was on the previous revenue flight of the test aircraft.

2.6.3 **Post Flight Data Analysis**

Flight test data was reviewed for indications of engine surge, flameout, and accel/decel capability differences from the engines operating with Jet A-1. The operation of engine #3 was compared across the ferry flight using Jet A-1 and the test flight with Bio-SPK blend. In addition, engine #3 operation was compared to the operation of the other three engines running with Jet A-1.

2.6.3.1 As the ferry flight and the Bio-SPK blend flight were different missions, only certain portions of the flight data are directly comparable. The Bio-SPK blend flight also included transient operation of the engine #3 that was not included in the ferry flight. A review of the data showed no indication of compressor stall or flameout. The acceleration and deceleration characteristics of the engines indicate no capability difference with the Bio-SPK blend. It is apparent that the test engine ran considerably hotter (~50°C higher EGT at idle) than the other engines. This is a sign of engine deterioration (the reference flight had the same behavior).

2.6.3.2 Throughout the flight, the engine showed consistent operation for the data recorded including N1, N2, EPR and fuel flow. Portions of the flight included transient operations (accelerations, decelerations, starting) of the engine #3. During all portions of the Bio-SPK blend flight, the engine #3 performed as expected with no operability related events noted.

2.6.3.3 The 747-300 Airborne Integrated Data System data was analyzed for the engine ground run and the test flight. No issues arose during the test flight with the engine #3 running on the 50% Bio-SPK blend. The aircraft and engine performance were as expected and the fuel blend gave similar results in operation to those found during ground based testing.

2.6.3.4 There was no obvious difference of main parameters between engine #3 and other engines. However, the engines are not well matched on main parameters due to horsepower extraction, bleed air, and primarily engine deterioration. There was no obvious sign that the Bio-SPK blend had any adverse effect on engine response. The aircraft was returned to service within one week, after subject engine change. The airframe has been monitored, and nothing abnormal has occurred.

3. LESSONS FROM THE TESTS

3.1 The different flight tests have demonstrated that flying a large commercial aircraft with a blend of drop-in alternative fuel, up to 50%, with conventional fuel was technically feasible.

3.2 They also demonstrated that a variety of alternative fuel feedstocks and refining processes could be envisaged. The primary criteria for consideration and evaluation for these fuels must be the characteristics of their performance in aircraft engines, fuel systems and aviation fuel infrastructures, rather than the feedstocks from which they are derived. These drop-in fuels can come from a variety of fossil and bio feedstocks depending on the most important issues in the country or region where the fuel is produced and used, including fuel availability and supply, fuel security and environmental characteristics such as air quality and greenhouse gas emissions. The tests also identified some early promising alternative fuel suppliers and enabled to draw attention of additional suppliers.

3.3 The tests provided some substantive information in the process of alternative drop-in fuel qualification and certification for use by the aviation industry. They played an important part in the works that lead to publication on September 28, 2009 of ASTM D7566 entitled “Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons”, which provides criteria for production, distribution, and use of aviation turbine engine SPK fuel produced from coal, natural gas, or biomass using Fischer-Tropsch (FT) process.

4. NEXT STEPS

4.1 Additional tests are necessary to demonstrate the possibilities of additional types and blend levels of alternative drop-in fuels for aviation and establish certification for their use.

4.2 Additional tests as part of an integrated programme using labs, rigs, engines, must be performed in order to demonstrate that the repetitive usage of alternative fuels does not create challenges that could not be identified with a single flight.

4.3 Further to the issuance of ASTM D7566, commercial flights can now be envisaged, with a blend of up to 50% FT SPK fuel with conventional fuels.

4.4 Very recently, on October 12, 2009, a Qatar Airways A340-600 equipped with four Rolls-Royce Trent 556 engines performed the world’s first commercial passenger flight with a 50-50 blend of synthetic Gas to Liquid (GTL) kerosene and conventional oil-based kerosene fuel, on the four aircraft engines. The more than 6-hour flight from London Gatwick (UK) to Doha (Qatar) is a major milestone in the development of drop-in alternative fuels for aviation. The flight was the latest step in over two years of scientific work carried out by a consortium consisting of Airbus, Qatar Airways, Qatar Petroleum, Qatar Science & Technology Park, Rolls-Royce, Shell and WOQOD into the benefits of using GTL Jet Fuel to power commercial aircraft. Much of this work is being undertaken at the Qatar Science & Technology Park in Doha.

4.5 Gas-To-Liquids fuels (GTL) show improvements in terms of local air quality (virtually sulphur free and with much less particulates) and a CO2 footprint comparable to that of conventional petroleum-derived kerosene. In addition a slight higher heating value should results in slightly lower fuel consumption.They constitute a readily available alternative fuel and are precursors to sustainable bio-jet fuels (eg BTL)

4.6 Additional work must be carried out to certify for use additional drop-in biofuels from different feedstocks and refining technologies, and to increase the approved blends for all alternative fuels, with the goal of having as many options of feedstocks, refining processes and blend levels as possible, certified for use.

4.7 For all of the above milestones, availability, affordability and sustainability of sufficient quantities of feedstock are necessary, together with the associated transformation technologies and facillities.

— END —