The History and Future of Aviation Fuels

Dr Alisdair Clark
Agenda

- Aviation Gasoline (‘AVGAS’)
  - History
  - Manufacture
  - Future
- Aviation Turbine Fuel (‘JET’)
  - History
  - Manufacture
  - Distribution
  - Future
- Summary
Early Aviation

- Sir George Cayley (1773-1857) Gliders
  - ‘Aerial Navigation’

- Clement Ader 1890
  - flew ‘Eole’ 200 meters
  - 20 hp steam engine

- Nicolaus August Otto 1876
  - 4 stroke gasoline engine

Source: Musée des Arts et Métiers, Paris
1903

- Wright Brothers 4 cylinder, 12 hp engine, 179 lbs.

- Early aviation engines low power/heavy.

- Early aviation fuels of low octane quality (ca. 60 MON) and specifications based on volatility/gravity.

Source: Smithsonian
Air and Space Museum, USA
Gnome Rotary Engine – 100 hp

Author: National Museum of the United States Air Force, USA
1910 – 1920 Engine Problems

- Wide variations in fuel (Dutch East Indian, Californian, Pennsylvanian crude oils).
- Engine operation unreliable.
- 1915 Green and Gibson (Farnborough)
  - Cooling important
  - Fuel/Air ratio important
  - Benzene doped fuels
- 1917 Dean (US Bureau of Mines)
  - Fuel should be ‘volatile’
- Dedicated specifications for Aviation Gasoline (‘AVGAS’) introduced.
Uncontrolled Combustion Damage

A few seconds of pre-ignition can do this.

Photo courtesy of United Technologies – Pratt & Whitney
### Early Aviation Engines and Fuels

**1918 First US Government Avgas Specifications:**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Export</th>
<th>Fighting</th>
<th>Domestic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td>Free from acid, water and suspended matter</td>
<td>Water white</td>
<td></td>
</tr>
<tr>
<td><strong>Colour</strong></td>
<td>Water white</td>
<td>Negative</td>
<td></td>
</tr>
<tr>
<td><strong>Doctor Test</strong></td>
<td>Negative</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Corrosion</strong></td>
<td>No grey or black corrosion in a copper dish and no weighable gum.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Distillation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% distillate °C</td>
<td>50 to 65</td>
<td>60 to 70</td>
<td>50 to 75</td>
</tr>
<tr>
<td>50% distillate °C</td>
<td>95 max</td>
<td>95 max</td>
<td>105 max</td>
</tr>
<tr>
<td>90% distillate °C</td>
<td>125 max</td>
<td>112 max</td>
<td>155 max</td>
</tr>
<tr>
<td>96% distillate °C</td>
<td>150 max</td>
<td>125 max</td>
<td>175 max</td>
</tr>
<tr>
<td><strong>End Point °C</strong></td>
<td>165 max</td>
<td>140 max</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total distillate % v/v</strong></td>
<td>96 min 2 max</td>
<td>96 min 2 max</td>
<td>96 min 2 max</td>
</tr>
<tr>
<td><strong>Loss</strong></td>
<td>2 max</td>
<td>2 max</td>
<td>2 max</td>
</tr>
</tbody>
</table>
The premise for aviation fuel specifications has remained unchanged from this time forward: to improve engine performance and the safety and reliability of flight.
Detonation and the Octane Scale

- 1919 Ricardo (Asiatic Petroleum Company) investigates engine combustion.
  - ‘The Internal Combustion Engine’ published 1923
  - Fuels resistance to detonation important.
- Similar study in US by Kettering
- Fuel must ‘wait for the spark’ and not explode uncontrollably in the engine.
Detonation

- Gasoline explodes rather than burns evenly:
- ‘Wait for the spark’
Tetraethyl Lead

- First aviation trial of TEL in AVGAS (1922) failed – lead fouling.
- Issue resolved with the addition of ethylene dibromide scavenger (‘TEL-B’).
- In 1930 US Army Air Corps specified first leaded AVGAS, 3 ml/USG TEL maximum, ≥87 ON.
- In 1934 British Air Ministry issued DTD-230 for leaded AVGAS, 4 ml/IG TEL max, ≥87 ON.

From this time forward, TEL-B has been a vital ingredient in achieving the high octane quality of AVGAS.
100 Octane AVGAS:
• 1930’s refinery technology limiting AVGAS potential.
• Typical performance AVGAS 87 or 92 octane.
• 1936 Birch and Tate (BP) discover H$_2$SO$_4$ alkylation – versatile and low cost route to manufacture an iso-octane rich component for AVGAS production.
• Rapidly adopted by the Industry.
• 1934 – no major suppliers of 100 octane AVGAS.
• 1945 – over 25 million gallons per day 100 octane AVGAS.
• Supercharge aviation rating combined with lean ‘MON’ rating in 1942 to give Grade 100/130.

In 1970’s ‘100LL’ introduced to rationalise Grade 80 & 100/130 infrastructure – now the most common Aviation piston engine Grade in the World.
## Engine – Avgas Development

<table>
<thead>
<tr>
<th>Date</th>
<th>Name</th>
<th>Hp/lb</th>
<th>cu in/Hp</th>
<th>Design</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1902</td>
<td>Wright Bros.</td>
<td>0.07</td>
<td>34</td>
<td>In-line 4</td>
<td>Petrol</td>
</tr>
<tr>
<td>1913</td>
<td>Gnome</td>
<td>0.37</td>
<td>8</td>
<td>Rotary 9</td>
<td>Petrol</td>
</tr>
<tr>
<td>1922</td>
<td>Curtis D-12</td>
<td>0.64</td>
<td>3</td>
<td>V-12</td>
<td>DAG</td>
</tr>
<tr>
<td>1937</td>
<td>PW Wasp-D</td>
<td>0.86</td>
<td>1.3</td>
<td>Radial 18</td>
<td>TEL</td>
</tr>
<tr>
<td>1945</td>
<td>PW Wasp-M</td>
<td>1.03</td>
<td>1.1</td>
<td>Radial 28</td>
<td>TEL/Alky</td>
</tr>
<tr>
<td>1945</td>
<td>RR Griffon</td>
<td>1.13</td>
<td>1.0</td>
<td>V-12</td>
<td>TEL/Alky/150PN</td>
</tr>
</tbody>
</table>

Author: National Museum of the United States Air Force, USA
The major challenge for Avgas in the world today is moving to an unleaded product:
- TEL used to enhance octane for over 80 years.
- Environmental concern growing / alternative options sought.

The Industry are working together for a solution / managed transition via the Piston Aviation Fuels Initiative.

In Europe mid-octane unleaded Avgas is already available.

In the USA the FAA aim to ensure ‘A replacement fuel for leaded aviation gasoline is available by 2018 that is usable by most general aviation aircraft.’

http://www.faa.gov/about/initiatives/avgas/

*The piston engine fleet is a unique and important sector of the Aviation Industry supporting global transport.*
History

Hero of Alexandria 1\textsuperscript{st} Century

Picture: Wikipidia
Early aviation development focused on piston engines burning aviation gasoline.

BUT achieving >3000 hp a major issue:
- up to 28 cylinders
- Many moving parts
- Vibration

A technical solution was needed...

In the mid/late 1930’s the aviation gas turbine engine was developed.

Such engines offer the performance and reliability which the world enjoys today:

“...nearly 2.7 billion passengers carried in 2010, .....$5.3 trillion worth of freight ....represents some 35% of the value of global trade, despite it representing half a percent of the volume. ...” ATAG Report 2012
1937: Testing at Thomsom-Houston, Rugby.
- Severe surging in the fuel system.
- Imbalance of flow at the vaporisers.
- Carbon blockage of vaporisers and nozzles.
- Carbon deposits in the flame tubes.
- Local overheating.

A key conclusion was that while the aviation turbine engine could burn many fuel types, for reliable, efficient operation a clean burning kerosine with low freeze point offered the best solution.

*Fuel specification RDE/F/KER introduced in 1944 then superseded by DERD 2482 in 1947.*
From this point forward aviation kerosine ‘Jet Fuel’ was developed and refined to give the product the world uses today under Def Stan 91-90, ASTM D1655 and related specifications.

As the demand for Jet has grown, the Industry has had to perform a careful balance to ensure global availability of a fit-for-purpose product:

- Engine Operability
- Performance
- Cost of Ownership

- Fuel Availability
- Testing requirement
- Cost of Production

Specification
Jet Fuel can be manufactured by essentially 5 routes:

- Distillation of crude oil to give a kerosene cut with or without additional ‘cleaning’ step.
- Hydrocracking of heavy crude oil fractions.
- Fischer-Tropsch ‘carbon to kerosene’.
- Hydrotreated esters and fatty acids.
- Converting sugar to hydrocarbons using microbes.

The Industry are working on additional routes and each has benefits/problems.

*It’s important to remember Jet fuel needs to be manufactured in many different countries to ‘join the peoples of the world’ and give a truly global transport system.*
In the last 24 hours typically:
- More than 90,000 flights will have operated.
- More than 6 million people will have been lifted to 7 miles height, transported at 500 mph through thin/cold air where it is impossible to survive unaided, and landed at destination.
- Jet fuel will have moved through the global distribution infrastructure at 8000 litres per second to meet this goal (high, but significantly less than ground fuels/power generation).

An efficient, quality controlled and well managed distribution system is necessary to ensure aviation engine / airframe technology can work as designed.

The Industry relies on the expertise of members to maintain standards e.g.
- $\leq 0.2$ mg/litre dirt into-plane.
- $\leq 30$ ppm ($\leq 15$ ppm ) free water into-plane.

In-house, JIG, IATA regulations critical.

Energy Institute guidelines ‘EI 1530’.
Numerous engineering and control criteria are required to meet Industry requirements.

By way of illustration, some examples from filtration:

- Microfilters
  - EI 1590
  - Source: Faudi Aviation

- Filter Water Separators
  - EI 1581
  - Source: Energy Institute

- Filter Monitors
  - EI 1583
  - Source: Velcon

Further details available from
Energy Institute 61 New Cavendish St,
London W1G 7AR
Industry research is active in this area:
- Filter design
- Static charge generation
- Trace water/dirt

Electrostatic Charge – CRC/EI Project

115 l/min
Electrostatic Charge – CRC/EI Project

- Field Meter Reading

Valve diverts flow to tank

Voltage climbs as electrons arrive and cannot dissipate to wall in time to exit via current meter

-1000’s Volts

Valve diverts flow from tank

Electrons slowly flow to wall and out Charge decays

Time
Some chemistry.....

\[ \text{C}_{10}\text{H}_{22} + 15\frac{1}{2}\text{O}_2 \rightarrow 10\text{CO}_2 + 11\text{H}_2\text{O} \quad \text{Combustion} \]

142g + 496g \rightarrow 440g + 198g

22% + 78% weight

Engines mainly burn air (oxygen) and some carbon/hydrogen is added to keep the reaction going. The aviator takes advantage of this by using liquid hydrocarbons and catching ~78% fuel weight from the surrounding air. This is a major challenge for say, a commercial electric aircraft.
To maintain a ‘licence for growth’ and in response to environmental pressure the aviation Industry are pursuing a whole range of options to minimise CO$_2$ emissions:
- Increased engine/airframe efficiency (fuel consumption per passenger mile – Airbus A380).
- Optimise flight routes (SESAR/NextGEN)
- ‘Green Airport’ initiatives.
- Emissions control / ICAO measures
- BioJet

A modern aircraft offers per passenger 74 miles/IG or 26 km/l

Source: IATA 2012 Review
Aviators have tried many different fuel types, e.g.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy MJ/litre</td>
<td>~ 31.8</td>
<td>~ 34.7</td>
<td>21.2</td>
<td>8.4</td>
</tr>
<tr>
<td>Energy MJ/kg</td>
<td>~ 44.2</td>
<td>~ 43.4</td>
<td>50.0</td>
<td>120.2</td>
</tr>
<tr>
<td>Flam. range mass Air:Fuel</td>
<td>26 to 4</td>
<td>22 to 4</td>
<td>34 to 10</td>
<td>345 to 5</td>
</tr>
<tr>
<td>Min. Ignition Energy mJ</td>
<td>-</td>
<td>0.30</td>
<td>0.28</td>
<td>0.019</td>
</tr>
</tbody>
</table>

None offer the inherent handling, safety and operational benefits of kerosine jet fuel, as first identified in 1944, for commercial operations.

*SNAG – If the Industry retains kerosine CO₂ footprint will increase while all other transport/power generation sectors de-carbonise to meet environmental legislation. How can this be solved?*
Answer: Make the fuel out of a renewable, sustainable, source:

CO₂ Cycle

Photograph: Qantas

Photograph: Kew

Photograph: UKPIA
www.ukpia.com
<table>
<thead>
<tr>
<th>Process</th>
<th>Feedstock</th>
<th>HC Type</th>
<th>Company</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT - Fischer Tropsch</td>
<td>Coal/Nat. gas/Biomass</td>
<td>Iso/normal paraffins</td>
<td>Sasol, Syntroleum, Shell, Rentech.</td>
<td>Approved</td>
</tr>
<tr>
<td>HEFA - Hydrotreated Esters and Fatty Acids</td>
<td>Triglyceride oils</td>
<td>Iso/normal paraffins</td>
<td>UOP, Syntroleum, Neste, EERC</td>
<td>Approved</td>
</tr>
<tr>
<td>FT-SKA- Fischer Tropsch Synthetic Kerosine</td>
<td>Coal/Nat. gas/Biomass</td>
<td>Iso/normal paraffins</td>
<td>Sasol</td>
<td>Approved</td>
</tr>
<tr>
<td>with Aromatics</td>
<td></td>
<td>+ 1 ring aromatics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSHC – Direct Sugar to Hydrocarbons</td>
<td>Sugar</td>
<td>Iso/normal paraffins + Aromatics</td>
<td>Amyris/TOTAL</td>
<td>Approved</td>
</tr>
<tr>
<td>ATJ – Alcohol to Jet</td>
<td>Sugar to alcohol</td>
<td>Iso/normal/cyclo paraffins</td>
<td>Gevo, Cobalt, Zeachem</td>
<td>Approved</td>
</tr>
<tr>
<td>Co-hydroprocessing at ≤5%</td>
<td>Triglyceride oils</td>
<td>Iso/normal paraffins</td>
<td>BP, Phillips66, Chevron</td>
<td>ASTM Task Force</td>
</tr>
<tr>
<td>SK – Synthetic Kerosine (Hydro-deoxygenation)</td>
<td>Biomass (sugar/corn)</td>
<td>Cyclo + other paraffins</td>
<td>Virent / Shell</td>
<td>ASTM Task Force</td>
</tr>
<tr>
<td>SAK – Synthetic Aromatic Kerosine</td>
<td>Biomass (sugar/corn)</td>
<td>Aromatics</td>
<td>Virent, Shell</td>
<td>ASTM Task Force</td>
</tr>
</tbody>
</table>

+ Various Other Proposed Routes
Electric?

– May see electric in GA for flight schools:

**HK 36 Super Dimona**

- Top speed: 220 km/h
- Wingspan: 9.5 m
- Length: 6.67 m
- Manufacturer: Airbus Group

Source: Airbus
Photograph: Telegraph Newspaper

- Hydrogen fuel cell / Lithium-ion Battery
- **HK 36 Super Dimona**
- 2 seats

Source: Farnborough Air Show
Photograph: Author
Electric?

- eHang personal transport
- 1 seat
- 4 x 4 x 1.4 meters
- 17 kW/h battery
- 152 kW maximum using 8 motors
- 60 km/hr cruise, ceiling 3000 feet (Dubai)
- 25 minute duration

Source: Aero Space
Royal Aeronautical Society
• Aviation fuels have been developed over the last 90 years with the specific objective of improving the reliability and safety of flight and are overseen by the Aviation Industry.
• Aviation Gasoline (‘AVGAS’) represents a high quality spark ignition fuel for aviation piston engines.
  – The future challenge for AVGAS is to transition to an unleaded fuel in the ca. 2018 - 2023 time-frame.
• Aviation Turbine fuel (‘JET’) represents a high performance kerosine for use in aviation turbine engines.
  – The future challenge for JET is to:
    (i) meet the demand of ~5% year growth in commercial use.
    (ii) satisfy environmental concern regarding CO$_2$ emissions while constrained to using a hydrocarbon fuel.
Thank You