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Review of Alternative Fuel Initiatives for Leaded Aviation Gasoline (AVGAS) Replacement

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Tetraethylead (TEL) is an additive in aviation gasoline (AVGAS) fuels to help suppress knock. Knock produces very high pressure inside the engine which can cause severe damage easily. Without the addition of TEL, the octane levels will be too low for some engines. Using a lower octane fuel than required level could lead to engine failure in piston aircraft engines. This is because Piston aircraft engines operate at higher power settings and temperatures. Friends of the Earth (FOE) filed a ‘‘Petition for Rulemaking Seeking the Regulation of Lead Emissions from General Aviation Aircraft Under Clean Air Act” to conduct a finding that lead emissions from general aviation aircraft endanger public health. FOE insisted to issue a proposed emission standard for lead from general aviation aircraft under the Clean Air Act (CAA). In 2008, EPA decreased the level of the primary National Ambient Air Quality Standard (NAAQS) for lead from 1.5 micrograms per cubic meter (µg m^{-3}) to 0.15 µg m^{-3} in order to provide increased protection for children and other at-risk populations against an array of adverse health effects. In this study, a comprehensive review will be conducted to analyse the replacement fuels introduced or tested or in use around the globe that has been used to further reduce or totally eliminate TEL from avgas 100LL. This paper assists aviation research students to further research and gain comprehensive knowledge on AVGAS, the problems on AVGAS and alternative fuel initiatives around the globe. If replacement for leaded fuels are tested and proven for drop-in replacement, the general aviation community can continue to thrive for decades to come with a renewable resource that is cleaner for the environment. Lead emissions should also be given equal concentration along with emissions of carbon dioxide, carbon monoxide, oxides of nitrogen and other particulates emissions in aviation with proper studies and findings to help the elimination efforts

1. History of Aviation Gasoline

Using leaded fuel to power aircrafts has been a common practice in the industry for the past 80 y but as the unburnt lead deposits in the engine have affected engine performance, the industry has been constantly researching and developing alternatives which will counter this adverse effect, simultaneously making the aviation fuel more economically and environmentally sustainable (Cloche, 2010). According to ASTM’s AVGAS timeline, from 1903 until 1922, all fuels used to power aircraft engines were unleaded, caused the engine to make ‘knocking’ sounds due to lower octane levels (Rothrock and Biermann, 1939). But in 1926, American Navy started using the additive Tetraethyl lead (TEL) by adding it directly into the fuel tanks. During that same period “the concept of an octane rating scale” was developed to see the performance of “fuels blended with TEL” compared to a “fuel that was pure iso-octane” (Ziulkowski, 2011). As this mixture was a blend of 87 % iso-octane and 13 % unleaded gasoline, it was named as 87MON based on its Motor Octane Number. MON grading system is still widely used in the automotive industry which allows the manufacturers to test fuels against the engine performance, generally initiating with the idea that the higher the MON rating, the

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better the engine performance (Ziulkowski, 2011). Since then until the present day, lead additives are blended in the AVGAS to enhance engine performance, but due its property of being an environmental pollutant, every consecutive year, oil and gas companies invest millions of dollars financing the research and development of an alternative aviation fuel which would be unleaded, affordable and able to optimize engine power (Waitz, 2004). General aviation (GA) industry which includes private flights, training flights, flying clubs, crop spraying, commonly uses aircrafts powered by small piston engines operating on the “same principles as spark ignition engines of cars” but require fuels with higher octane numbers for better performance (Shell Global, 2017). In a detailed Kitplanes manual designed by Paul Millner, it is explained that “AVGAS is difficult to make and hence is expensive” (Millner, 2006). Since the early 1900’s, many grades of AVGAS were used for “reciprocating piston powered engine”, such as 80/87, 91/96, 100/130,108/135 and 115/145 but as of this date “there are only two main AVGAS grades (100 and 100LL)” available in the general aviation industry which contain low lead contents but their production volume too is decreasing worldwide (Shell Global, 2017). AVGAS 100LL is blue in colour while AVGAS 100 is green in colour. Motor Octane Number (MON) is used to classify the various grades for AVGAS. In the book From the Ground Up, 1964 it is explained that two rating systems are used to name the grades, for instance 100/130; “The first number indicates the octane rating of the fuel tested to aviation lean standards, which is similar to the anti-knock index or pump rating given to automotive gasoline in the US.” The second number is for “the octane rating of the fuel tested to the "aviation rich" standard, which tries to simulate a supercharged condition with a rich mixture, elevated temperatures, and a high manifold pressure” (McDonald, 1964). For 100/130, the fuel has the octane rating of 100, which is maximum in this case, at its “lean settings” and “130 at the rich settings used for take off” and other situations where full power is required. But as the manufacturers developed more AVGAS grades over the years, the classification and identification was limited to the octane number in lean settings and hence 100/130 is now just known as AVGAS 100. Its modified version with low lead contents, 100LL has received ASTM D910 and UK DEF STAN 91-90 specifications for its usage in small aircrafts worldwide (Shell Global, 2017). Avgas 100LL contains 0.32 to 0.53 g TEL per litre (Experimental Aircraft Association, 2009) which is 0.56 gL^{-1} of lead (Shell Global, 2017). A complete ban on the usage of lead in aviation fuels currently seems like an unlikely possibility because lead is the cheapest and most readily available source which acts as an octane boosting additive and anti-knock agent, saving the aircrafts from engine failure and ensuring safe, smooth and affordable flights (Cloche, 2010). First introduced in 1923, the lead levels have been reduced greatly in the AVGAS due to high risks of lead poisoning and environmental damage. “A 1985 EPA study estimated that as many as 5,000 Americans died annually from lead-related heart disease” (Kitman, 2000). In 1986, the American government decided to ban lead usage completely in automotive fuels. This was termed as the ‘phase-out of leaded gasoline’ (Totten, 2004). Sadly, lead usage in the general aviation industry continued and still continues.

2. MOGAS

Motor gasoline (MOGAS) or Automobile gasoline (AUTOGAS) has been an alternative to leaded fuel since 1964 when Experimental Aircraft Association (EAA) began testing on it. In 1982, the first flight of a Cessna 150 with a Continental 0-200 engine showed great results. In order for MOGAS to be used in aircrafts, engine and air frame modification which should be approved via Supplemental Type Certificate (STC) authorisation issued from Federal Aviation Administration (FAA) is mandatory. These modifications, such as the replacement of fuel pumps or fuel line delivery systems ensure that the aircraft is compatible with MOGAS. To date, 70,000 STC’s have been issued for aircraft modification for the use of MOGAS and the results have shown that MOGAS is “better for internal engine parts and fuel systems as compared to 100LL” (Cloche, 2010). When MOGAS is used in lower rated octane engines, it was seen that fewer spark-plug fouling issues occurred with less valve sticking as compared to when these engines are pumped with AVGAS 100LL. According to EAA test reports, “engines running on MOGAS have better extended life and more time between overhauls” (Engine overhaul, 1996), (Cloche, 2010). For best engine performance using MOGAS, the MON number must not fall below 80 as this might affect engine efficiency and internal temperatures. Not only is MOGAS is an efficient and unleaded fuel which when used in a modified engine like Continental 0-200 ensures safe and smooth flights, but it is also cost effective and cheaper than AVGAS 100LL. In USA, it is USD 0.34 per litre cheaper than AVGAS (Cloche, 2010). But at the turn of the millennium, further testing with MOGAS as an aviation fuel exhibited MOGAS to have a few operational issues as compared to its leaded counterpart, 100LL. This is because firstly MOGAS is said to stick more in the piston engine valves because of the soft metal alloys used to make valves and the angles they are set at. Secondly, MOGAS can cause frequent vapour lock because of its higher volatility at higher altitudes and hot temperatures. This shows that the limitation with airplanes running on MOGAS is that these are not designed to be used at higher altitudes because not only does the change in pressure creates air pockets leading to vapour locks but a phenomenon known as carburettor icing which can lead to partial or total loss of engine power (Cloche, 2010). Carburettor icing is caused when the fuel in the carburettor vaporises on higher altitudes and lower air pressures causing the release of latent heat and solidifying the fuel in the engine. Another problem associated with the use of MOGAS is its discouragement by the engine manufacturers as it does not go through the same quality assurance testing procedures like the aviation fuels and therefore it becomes an issue of liability. "Even though the FAA has publically approved of its use", the lack of quality control measures for MOGAS make its usage a risk for engine manufacturers as all the modifications done to the aircraft might not necessarily be compatible with the MOGAS used. As for the AVGAS, on the other hand, the entire set of fuel production and delivery is well maintained and expensive and all the tanks and delivery systems are properly cleaned to avoid cross-contamination as lead is highly reactive with water and oxygen, forming lead oxide and hydroxide (Hemighaus et al., 2006). According to Aircraft Owners and Pilots Association (AOPA), 2008, it is estimated that 51 % of the MOGAS which is available in the USA contains ethanol which hampers the engine functioning as "ethanol is incompatible with aircrafts' fuel delivery system" (Cloche, 2010). If the aircraft engine is exposed to ethanol, as explained by EAA, it could require a sum of USD 10,000 to repair the damage done in fuel lines, metal fuel bladders and pumps. In the long run, as the production of MOGAS exceeds that of AVGAS, it will be readily available for its usage in aircrafts, powering almost 70 - 80 % of General Aviation fleet (Cloche, 2010).

3. 82UL

The idea of 82UL was proposed in 1988 in Baltimore, during a Future Fuels for General Aviation Symposium with the "purpose of finding an unleaded aviation gasoline that can fuel the largest number of aircraft possible" (Ziulkowski, 2011). As until then TEL was viewed as the only additive that could boost octane number and enhance engine performance, it was decided that in order to use unleaded additives to the fuel, 82 octane was the furthest that the engine could take without causing the knocking effect. In the tests that were conducted, sixteen separate blends were prepared using 82 iso-octane. The iso-octane was used as an additive more like how TEL deposits were added in the 100LL AVGAS. To this, "specific aliphatic ethers, synthetic hydrocarbons or aromatic hydrocarbons" were added (ASTM International, 2004). These were termed as oxygenates as it helped to increase the oxygen content of the gasoline. These oxygenated were found to be the perfect replacement for TEL additives and so, an unleaded alternative was discovered. It was specified that the ether content in 82UL should be limited to 2.7 % by mass. Although the fuel met the 1990's Clean Air Act Amendments because of its zero lead content but the Environmental Protection Agency (EPA) gave its verdict against the fuel stating that the ether oxygenates dissolve easily in the water and do not cling very well to the soil, allowing it to migrate faster and farther in the ground as compared to other gasoline, and hence more likely contaminating the ground water and fresh water resources. As the fuel was not easily bio degradable, it was much more difficult and costly to clean it from the ground water. The 1996's Methyl Tertiarybutyl Ether (MTBE) contamination incident in Santa Monica, USA occurred because of its usage in the automobile fuel as a replacement to lead. Countless hours of test flights and fuel blends concluded that in order for a wide scale production and usage of 82UL in the general aviation industry, the aircraft needed structural and operational modifications because the fuel was not compatible with the engines found in a "low octane demand aircraft" (Ziulkowski, 2011). In 1988, 82UL received an ASTM D6227 specification which allowed it to be produced commercially and was dyed purple for identification. But strict guidelines were given and only engines that were tested and had received approval from the National Certifying Agencies were allowed to be powered by 82UL. Until 2004, 82UL held its ASTM specification and was believed to be a drop in fuel for AVGAS. Unfortunately, it was never produced on a commercial level by any of the world's oil refineries. If made readily available, 82UL could power 70 % of the general aviation fleet which makes up almost 30 % of the world's total AVGAS consumption (AOPA, 2008).

4. Hjelmco Oil 91/96

In 1981, a Swedish family lead by its member Lars Hjelmberg, founded the Hjelmco Oil, Inc. which manufactures unleaded and low toxic AVGAS (Hjelmco Oil, 2017). Hjelmberg was always concerned about finding an affordable alternative to leaded AVGAS. His research took him to realise that in Russia, the AVGAS was cheaper as compared to Europe. He noticed this because the fuel was unleaded and was produced in greater volume. He created 91/96 Hjelmco oil, an unleaded and transparent AVGAS. It contains Ethyl tert-butyl ether (ETBE) which is an oxygenate that is blended into AVGAS. It contains an extra oxygen in the chemical so when it is mixed with regular AVGAS, it adds more oxygen to combine with hydrocarbons resulting in a much cleaner burning fuel (Ziulkowski, 2011). As it does not require any STC approval on engine modification, it is produced commercially and is readily available in the market. In reality it is an improvised version of 80/87 unleaded AVGAS or 80UL. In as early as 1995, prominent engine manufacturers like

Lycoming, Rotax and Teledyne Continental approved the usage of Hjelmco 91/96 in their engines. This grade of gasoline complies with all of the ASTM D910 standards except for its colour and lead content (Cloche, 2010). 91/96 UL is 10 % cheaper as compared to leaded fuels because its transportation and maintenance gets reduced thanks to its zero lead content. Leaded fuels require unreactive, clean metal tanks and pipelines which should be checked for cross contamination regularly. It is majorly distributed in Sweden and now even shipped to Japan through a franchise type retail business model which allows it to be exempted from value added tax. This reduces the cost of the fuel for the consumers. Another advantage enjoyed by this fuel in Sweden is the Swedish Aviation Authority's stand which "allows engines using this fuel to increase their Time Between Overhaul (TBO) by an additional 50 % which significantly reduces maintenance work and operating costs" (Cloche, 2010). Compared to its previous version 80/87 UL, 91/96 UL received a much warmer welcome in the market for the following reasons; firstly it was unleaded and complied with the Swedish legislation of environmentally friendly fuels. Secondly, the fuel had a much higher octane rating as compared to 80/87 UL and therefore enhanced engine performance at a cheaper price as compared to regular AVGAS. Thirdly, at the time of its launch, oil refineries were more adamant over finding a one fuel solution for the aviation industry instead of using blends and were willing to install the facilities such as delivery tanks, pipelines and nozzles that were custom made for 91/96 UL (Cloche, 2010). But despite all its positives, Hjelmco Oil never received enough support to be produced and distributed worldwide. This was because Hjelmberg never applied for the fuel to be patented and so his company reserves the sole rights for the manufacturing and distribution of 91/96UL. Another reason for this is the fact that in USA, until now there are no laws barring the use of lead in aviation fuels and that is the reason why 100LL still remains to be the most popular choice. It is argued that even though the octane rating of Hjelmco Oil is high, it is not high enough to boost the engine to reach a power supplied by 100 and 100LL. "In its current form it cannot cover the 30 % of GA fleet that consumes most of the AVGAS and needs all of the octane boost" (AOPA, 2008), but it was suggested by the company that environmentally friendly octane boosting additives were being researched upon to be added to 91/96UL to give a similar result as that achieved in the case of 100LL (Cloche, 2010).

5. Swift Fuels 100

In April 2008, a new synthetic fuel derived from bio feed-stock was launched by the Swift enterprise that had a "higher than 100 octane number" and was claimed to be the most accurate and perfect replacement for leaded 100LL (Swift Enterprises, 2008), (Cloche, 2010). Swift Fuel 100 (SF100) is a binary fuel containing only two chemical components which has a biomass source and an oxygenate with an octane rating higher than or equal to 92. To produce this fuel, first a biomass source rich in carbohydrate like sugar beets, switch grass or plant's waste products is needed. Chemical reactions converts this waste material into an oxygenate or alcohol which has a motor octane number of 136 (Cloche, 2010) The second product which is obtained during the refining process and contains a motor octane number of 92 is blended with the 136 octane component to give a resulting mixture MON 102. Hence a fuel better than 100LL is created. John Rusek, who is the co-founder of Swift fuels defended the fuels stance by saying that as in the case of other biofuels and biodiesels, Swift Fuel 100 (SF100) is safe from any kind of yeast or bacteria contamination giving it a longer shelf life. This is because "the last two steps in the refining process expose the components to high temperature reactors" which kills all the bacteria and fungus (IATA, 2009). In 2009, it was declared the SF100 meets the ASTM D910 standards and its full detonation testing showed that fuel had much better anti-knocking properties as compared to 100LL. Further comparison of SF100 with 100LL exhibited the fuel to be heavier but releasing higher energy content that was 3.43 % more per litre as compared to 100LL (Atwood, 2009). And because of this, "the fuel volumetric flow of 100SF, compared to 100LL was reduce by 8% giving it a better range and power output" (Cloche, 2010). The only engine modification required for the usage of 100SF is the change in ignition timing with an advancement of 3 degrees so that the fuel gets enough time to "burn properly in the combustion chamber" (Cloche, 2010). Results of 'endurance tests ' conducted during the test flights using higher temperatures showed that at 50 degree Farenhite, 100SF had a "consistent higher exhaust gas temperature" (Cloche, 2010). As the fuel is still in the certification process with numerous test flights being conducted on Cessna 172 fleet and Teledyne Continental, its manufacturing at commercial level remains on hold. The founders of the fuel have notified the industry that as the production of the fuel requires only a three step refining process, production of 100SF in large volumes will be economical (IATA, 2009). It was further stated that unlike other petroleum products and AVGAS, 100SF does not rely on the changing fuel prices in the oil market as its made from the raw material biomass which can be anything from sugar cane to plant waste, as long as it has a high carbohydrate content, reducing the dependency on one resource (Cloche, 2010). The pricing for SF100 is estimated to be USD 15.85 – 17.17 per litre but the company predicts for this to drop once refineries approve bulk production of the fuel. Hoped to be the renewable and sustainable unleaded alternative to 100LL, SF100 uses pure hydrocarbons 1,3,5-trimethylebenzene (Mesitylene) which is an aromatic hydrocarbon and 2-methylbutane (Isopentane) which is a branched chain alkane, mixed in a ratio of 80 : 20 to produce SF100 also known as 102UL (Ziulkowski, 2011). In April 2011, Swift fuel 102UL received an authorised ASTM D7719 standard specification for "High Octane Unleaded Test Fuel" but a final verdict from the task force assembled for the purpose of giving SF100 an approval for commercial manufacturing is yet to be given (Ziulkowski, 2011). Another added benefit of the Swift fuel is that as it is derived from 100 % natural products giving it the chemical property of being non-hazardous, it can be transported using the same tanks, pipelines and oil tankers which are commonly available on the air field and in hangars. This will further reduce the cost as additional equipment and facilities are not required to be purchased or built (Hirschman, 2009).

6. G100UL

Another entry into the unleaded fuel list was made by General Aviation Modifications, Inc. (GAMI) which is a research center conducting its own flight tests and certification assessments on alternative aviation fuels. G100UL which was introduced in December 2009, was claimed to be the ultimate solution and replacement to leaded 100LL avgas (Cloche, 2010). The fuel is said to meet the maximum octane requirements to boost engine performance, eliminate the knocking effect and has proper detonation properties. According to the center based researchers, G100UL does not contain any toxic compounds but it does require one raw material which is not being produced by any oil refineries. For the mass scale production of this fuel, an oil refinery will need 180 degree renovation and infrastructure replacement where the equipment and machinery will have to be built from the scratch to support the chemical process required. Until that is feasible, G100UL can be blended with 100LL AVGAS to give a 3.5 % better range in the likes of a "transparent drop-in solution" (Cloche, 2010). It is to be noted that before G100UL receives an ASTM certification and FAA approval, it will have to be undergo STC testing to display that engine and airframe modifications are possible to perfectly adapt to this AVGAS grade. So far, the STC application has been submitted for its tests on turbocharged Cirrus SR22 (Cloche, 2010).

7. AGE 85

The origin of Aviation Grade Ethanol 85 (AGE85) dates back to 1925 when the founder of Ford Motor company, Henry Ford said that "ethyl alcohol was the fuel of the future" with the power for the fuel to be derived from everyday fruits and vegetables (Ziulkowski, 2011). AGE85 is a fuel which is made up of 85 % ethanol, 1 % biodiesel, gasoline and other additives derived from bio feedstock and 12 % of pentane isomerate. Pentane isomerate's high vapor pressure helps to offset the lower vapor pressure of ethanol (Ziulkowski, 2011). Naturally ethanol has high octane ratings therefore it was viewed as a suitable replacement for 100LL (Mohsin et al., 2017). Ethanol is a type of biofuel that acts as alcohol-based alternative fuel, which is produced by fermenting and distilling starch crops that have been converted into simple sugars (Mohsin et al., 2017). With most of the research and development of AGE85 taking place in the University of South Dakota, USA, it was decided to apply for its ASTM specification in June 2005 but unfortunately, until this date, the ASTM standard approval hasn't been issued for the biofuel (Cloche, 2010). As in the case of other unleaded gasoline, AGE85 too requires STC approvals for appropriate structural and operational modifications to be made to the aircraft. But test flight carried out on Cessna 152, 180 and 182 engines showed that the fuel meets the octane level and is resistant to detonation. But the application of this AGE85 as an aviation fuel is not as easy as it looks because a huge sum estimated to be billions of dollars could be invested in testing and improvising the fuel, but the fact remains that ethanol is corrosive especially if it gets contaminated with water molecules (Cloche, 2010). Test flights showed that when the percentage of water is more in the ethanol blended fuel, it tends to sink at the bottom causing a separate layer of fuel at the top and water at the bottom, a phenomenon called phase separation. "This can cause damaging power surges when the fuel mixture goes from the water and ethanol layer to a rich gasoline layer resembling a high power setting and suddenly speeding up the engine" and eventually causes sudden loss of power and imminent engine failure (Johnson, 2006). Another operational problem associated with AGE85 fuel is the fact that in order to produce similar power as that by 100LL a higher fuel flow or rate is needed which would be 30 - 48 % more than the one needed when using 100LL. For this reason, engine modification, which requires bigger holes to be drilled in the fuel tank so that more fuel can pass through in a particular given time (Cloche, 2010). When left idle in the fuel tank, ethanol begins to separate into its distillates according to the relative weights and this could result in major disaster because it will delay the engine ignition when the aircraft is started after a long time. Also in low temperatures like 20 °F and below, the engine won't start because ethanol has a lower Reid Vapour Pressure (RVP) as that of 100LL. In this case engine pre-heating will be needed (Johnson, 2006).

Until this date, the fuel has neither received the ASTM certification nor an approval to be produced commercially in oil refineries (Cloche, 2010).

8. Conclusion

With proper understanding on aviation fuel types, development process and certification process, aviation researchers can appropriately evaluate alternative fuels for aviation industry. A good platform exists for alternative fuel transition for piston aviation engine. It is evidenced by Environmental Protection Agency (EPA) and Federal Aviation Administration (FAA) who are searching for alternatives to eliminate TEL from AVGAS. With TEL in AVGAS, spark-ignited, piston powered aircraft are able to meet minimum performance standards set by FAA; effectively making the light general aviation aircrafts airworthy but with greater impacts to the health and environment. Conventional bio-based fuels such as ethanol do not meet the performance standards of the FAA as well, with high potential for water content leading to catastrophic engine failures. As replacement fuels are tested and proven, the sustainability of general aviation community can continue to thrive by introducing renewable resource that is cleaner for the environment.

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