Alternative Fuels to Reduce Lead Emissions from Piston Engine Aviation

Words: 3564

Abstract

Lead is a toxic metal that poses many health risks if it enters the human body. The largest source of lead emissions in the United States is the burning of leaded aviation fuel, 100 Octane Low Lead (100LL/Avgas). Avgas has yet to be phased out because no alternative fuel with comparable or better performance has been identified to replace it. In this study, a variety of fuels were examined to determine a possible alternative. Fuels were examined based on their RON (Research Octane Number). The study was conducted as a systematic literature review through peer reviewed papers. Toluene and 2-Phenylethanol were found to have the highest octane ratings of 118 and 110 respectively. They are therefore the most promising potential Avgas replacements and deserve further research.

Introduction

Lead is a heavy, bluish-grey metal that is quite abundant in nature. It is used in many everyday items such as batteries, roofing, weights, bullets, etc. It is also used in many industrial processes such as cablesheeting, ballast tanks on ships, radiation shielding, etc. Another major use of lead is in aviation fuels.

Lead has been used in combustion fuels since their creation in the 1920's due to its ability to raise fuel's antiknock quality which is a fuel characteristic measured by octane rating that describes a fuel's ability to resist fuel detonation. Fuel detonation is when the fuel inside an engine cylinder explodes instantaneously instead of burning steadily. The larger the fuel's octane rating, the better its antiknock quality and the more smoothly the engine will run using it. Detonation is detrimental for the engine because it causes the gas to expand much more rapidly, not allowing time for the piston to be pushed out unevenly. The lack of space results in additional pressure exerted on the intake valves, exhaust valves, and piston. This can lead to component damage and engine failure, one of the biggest concerns for aircraft. Most automobile fuel has an octane rating from 87 to 93 depending on state gas laws. The most commonly used fuel in piston engine aviation, Avgas (100LL), has an octane rating of 100. While lead increases the antiknock quality of fuel, it also has negative effects as its emissions from burning are toxic to humans and animals.

Once emitted into the air, the lead particles can be inhaled and enter the bloodstream through the lungs. If food or water is contaminated, lead can also enter the body through the digestive tract. Some of lead's effects on the human body include: behavior and learning problems, lower IQ, slowed physical growth, as well as hearing problems, anemia, hypertension, and reduced kidney function, as has been reported by the Environmental Protection Agency (EPA) numerous times (U.S., Environmental Protection Agency, 2017). These effects are especially prevalent in small children exposed to lead.

Despite attempts to reduce lead emission levels, lead can still be found in children's blood today (Figure 1). A study looking into how lead interacts with the body led by Robert Brochin (2008) reported that three percent of children in the United States have high levels of lead in their blood. The study also stated that as many as twenty six percent of children in America could be experiencing harm from lead exposure (Brochin et al. 2008). While the atmospheric lead levels have been dropping, since lead emissions from automobiles were addressed, lead is still present in the air. This is still a significant problem for humans as it can both be directly breathed in and indirectly enter the food chain.

In pregnant women, lead has been found not only to cause the previously mentioned symptoms such as hypertension and anemia but also cause reduced fetal growth rate and premature birth, which harms both the baby and the mother (U.S., Environmental Protection Agency, 2017).

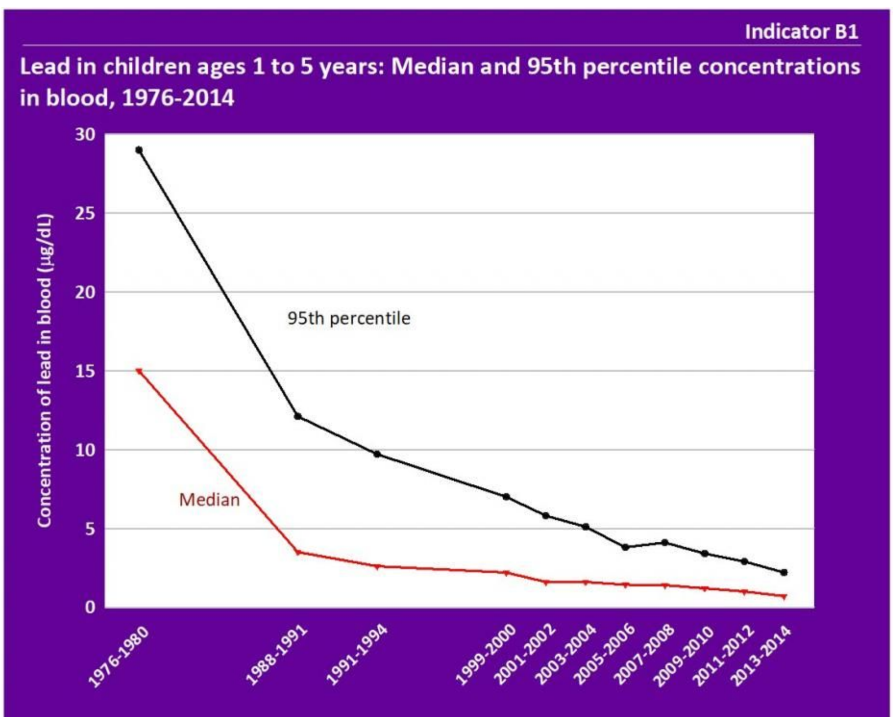

Figure 1. Lead levels in children's blood from 1976-2014 as reported by the EPA in 2017 (U.S., Environmental Protection Agency, 2017).

In recent years, the negative effects of lead have been highlighted in the Flint water crisis. When switching to a new water supply to save money, the city of Flint, Michigan went to a supply that was more acidic than the previous one. The increased acidity corroded many of the pipes that contained lead. That lead then entered the water supply where it was consumed by people. During this time, it was found that the percent of children with dangerous levels of lead in their blood rose to 10.6% resulting in many long term health problems for the affected children. While this lead exposure was not airborne, it demonstrates the negative impact of lead.

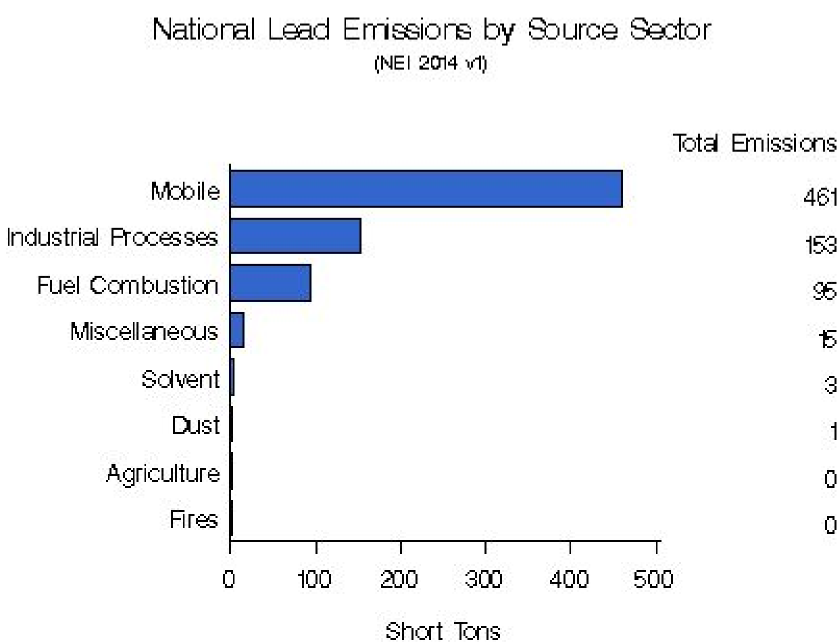

Figure 2. Tons of lead emissions produced in the US in 2014 by source. Mobile refers to vehicles and is the focus of this study. Fuel combustion refers to the emissions from stationary sources, such as generators. (U.S., Environmental Protection Agency, 2015).

In the past, attempts have been made to bring down the level of lead emissions, and thus reduce exposure from airborne emissions. In the early 1970s, the lead emissions from cars burning leaded gasoline increased the atmospheric lead levels to such a level that in 1973 the EPA addressed the issue by requiring that lead be phased out of automotive fuel by 1996. Between this legislation in 1973 and the final banning date in 1996, lead emissions were reduced in the U.S. by 98% (U.S., Environmental Protection Agency, 2017). As shown in Fig. 1, during this time period of reduced emissions that there was a corresponding reduction in lead lead levels in children's blood.

Since lead emissions from automotive fuel have been removed, attention is turning to removing other sources of lead pollution. Figure 2 shows that mobile emissions such as planes and ships make up the majority of lead emissions.

Aircraft are still allowed to use leaded fuel because of the high performance requirements of aviation engines to prevent the problems with detonation and engine failure mentioned above. Aircraft engines require higher performance fuels than cars because they typically operate in more diverse conditions, including operation at 10,000+ ft above sea level where lower air density results in reduced engine performance.

In the past, attempts have been made to reduce lead levels in aviation fuel. In the years following World War 2, 115-Octane fuel was the standard fuel in piston aviation, which contained more than twice as much lead as Avgas, as was stated in a report looking at the history of Avgas and how it might be used in the future (Kessler, 2013). In the late 1950s, Avgas began to be produced. Avgas's lower lead concentration made it a more environmentally friendly fuel, but it still contained lead.

Although mobile sources make up the largest source of emissions (Figure 2), the single largest contributor of lead emissions is leaded fuel in aviation, which make up 50% of lead emissions in the U.S. as was reported in a 2011 study investigating the correlation between the level of lead in children's blood, and their homes proximity to an active airport. The lead concentration of children’s blood was compared to their proximity to an active airport. Children around sixty six airports in North Carolina were compared (Miranda et al. 2011).

The populations most critically affected by lead emissions from aviation are people living within 500 m of an active airport; within this radius, people were found to have roughly 4.4% higher levels of lead in their bloodstream compared to those living further from an airport (Miranda et al. 2011). However, if atmospheric lead levels do not decrease further, people living near airports will continue to have health problems due to the lead emissions.

There are two types of lead poisoning: Acute toxicity and chronic toxicity. Acute toxicity is when someone is exposed to a large amount of lead over a short period of time. Chronic toxicity is when someone is exposed to a lower amount lead over a longer duration of time. Both types are harmful to humans.

This study aimed to find fuels that have a sufficient octane rating to replace Avgas. To be considered as substitute fuels, fuels needed to be higher performance than Avgas and have no lead content. Currently, fuels that are being considered as substitutes for Avgas are 2-Phenylethanol fuel (McCormick et al, 2015; Shanker et al, 2017; Tian et al, 2017), SuperButol (Kalamaras et al., 2017; Rankovic et al, 2015; Bedon et al, 2016), Ethanol (Bedon et al, 2016; Bourhis et al, 2016; Shanker et al, 2017; Vallinayagam et al, 2017; Wang et al, 2017), and

Toluene (Shanker et al, 2017; Tian et al, 2017; Vallinayagam et al, 2017). The fuels were compared by using their Research Octane Numbers (RONs), which indicate the octane rating of a fuel.

If an unleaded type of fuel with characteristics similar to Avgas is identified, it could then be the new primary fuel used by piston engine aircraft. Without lead emissions from piston engine aircraft, total lead emissions in the U.S. are projected to decrease by roughly 50% (Miranda et al. 2011). This would reduce the human exposure to lead in the atmosphere, therefore decreasing the amount of lead in their bloodstream and preventing health problems due to lead poisoning.

An important distinction to make is that this study focused on piston engine aircraft. There are several different types of aircraft engines including turboprop and jet engines. These other engine types use a kerosene based jet fuels, the most common being Jet A. These jet fuels do not contain lead and do not run in piston engines. They were therefore not relevant to this investigation.

Purpose

The purpose of this investigation was to identify a potential replacement fuel for Avgas that does not contain lead, so as to significantly decrease the lead emissions from aviation. This fuel must have an equal or greater octane rating than Avgas so as to not compromise aircraft engine performance. Additionally, fuels should not have any lead content. Fuels that met these criteria can be researched further to be considered as candidates to replace Avgas. Octane rating was the only factor considered in this study.

Research Question

Are there alternative non-lead fuels that provide equivalent performance to Avgas, so as to be capable of replacing it as the primary fuel used in piston engine aviation?

Hypothesis

Alternative hypothesis: There are alternative non-lead fuels that provide an equivalent octane rating to Avgas.

Null hypothesis: There are no alternative non-lead fuels that provide an equivalent octane rating to Avgas.

Methods

This study was conducted through systematic literature review of many peer-reviewed journals and articles. The data was collected on the RON values for different fuels. These values indicate the octane rating of a particular fuel. Literature was retrieved through online databases including JSTOR, ScienceDirect, Open Science Directory, EBSCOHost, and Science Archive. Access to literature from these databases is granted through Thousand Oaks High School, mentors with PhDs in scientific disciplines, and the California State University Channel Islands library. The Literature review commenced from August 2017 to December 2017, while data collection and systemic analysis took place from February 2018 through March 2018. Data collected was obtained from previous scientists research. Data was entered into and analyzed using Excel.

Some search terms used when looking for articles included RON, Octane, Fuel, Knock, Anti-knock, and lead. Throughout the literature review, four fuels were selected for consideration to replace Avgas: 2-Phenylethanol, Ethanol, Sueprbutol, and Toluene. For each fuel, data was collected from at least three peer reviewed papers to ensure accuracy.

Data collection was completed by analyzing different articles and compiling octane ratings to create a data set. Octane ratings were stored in a data table by fuel type. The mean of the octane ratings found for each fuel were taken as that fuel's octane rating. The means were then plotted in a bar graph. The standard deviation for each fuel was calculated and added to the graph in the form of error bars. The fuels with the highest octane ratings were then determined by comparing the ratings to Avgas through the graph. If multiple fuels had a high enough octane rating, the top two would be taken for further analysis.

Results

The four fuels that were compared to Avgas are 2-Phenylethanol, Ethanol, Sueprbutol, and Toluene. When analyzed, 2-Phenylethanol's octane rating was reported at 111 (McCormick et al, 2015), and 110 twice (Tian et al, 2017; Shankar et al, 2017). These values returned a mean octane rating of 110.33 with a standard deviance of 0.577. Ethanol's octane rating was reported at 107 (Wang et al, 2017), 109 (Vallinayagam et al, 2017), and three times at 108 (Shankar et al, 2017; Bourhis et al, 2016; Bedon et al, 2016). The mean octane rating came out to be 108 with a standard deviance of 0.707. Superbutol's octane rating was reported at 106.6 (Kalamaras et al, 2017) and 107 twice (Rankovic et al, 2015; Bedon et al, 2016). Its mean octane rating was 106.86 with a standard deviance of 0.231. Toluene's octane rating was reported at 116 (Tian et al, 2017), 118 (Vallinayagam et al, 2017) and 120 (Shankar et al, 2017). These values gave Toluene a mean octane rating of 118 and a standard deviance of 2, the largest variance out of all the fuels.

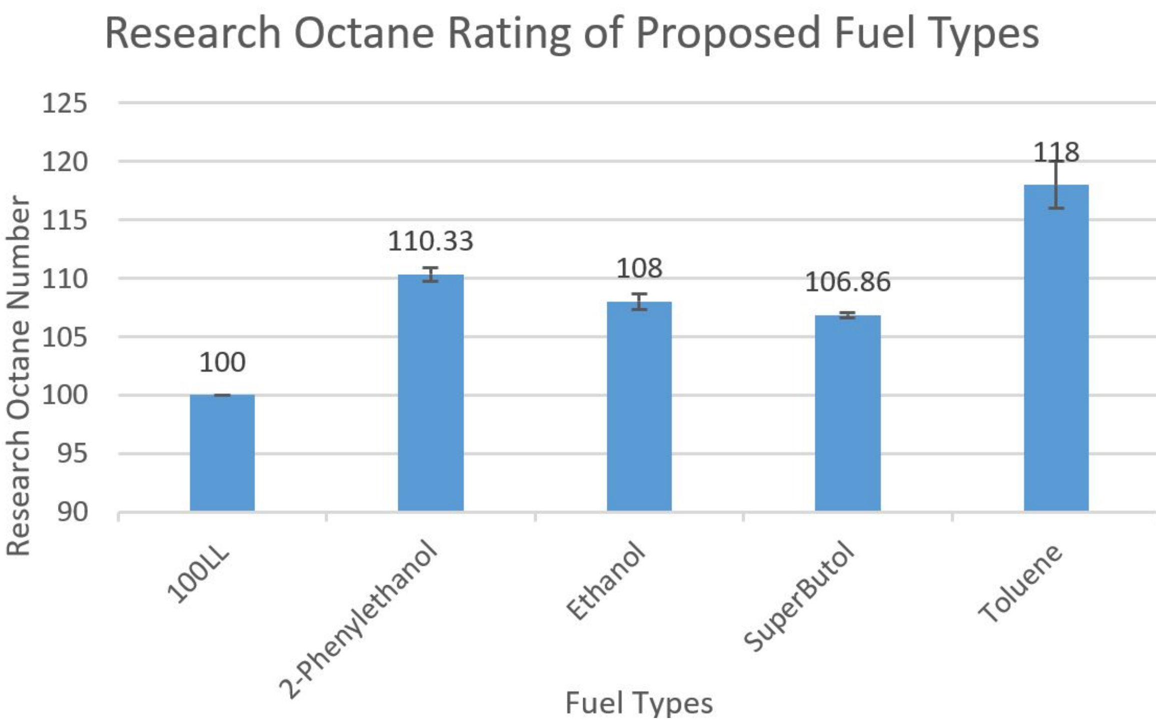

Figure 4. The *x*-axis shows different fuel types investigated and Avgas for comparison. The *y*-axis shows the mean octane rating of each fuel. The standard deviation for each fuel is given as an error bar.

Discussion

The first thing that should be addressed is all the proposed fuels had higher RON values than Avgas. This can be attributed to the fuels that were chosen with higher performance than automotive gasoline. All the fuels considered had to be high performance because any low performance fuel would not have a high enough octane rating to compare with Avgas, and could be easily eliminated. Since all the fuels were high performance, there was a high probability that the selected fuels would have a high enough octane rating to replace Avgas.

All considered fuels also did not contain any lead. This was not a difficult criteria for most fuels since they were originally made to meet the automotive requirement of having no lead. With lead removed from aviation fuel, the lead emissions in the U.S. would be cut in half. The atmospheric lead levels would then drop, reducing the quantity of lead people are exposed to. Reduced lead exposure would lower the concentration of lead in people's bloodstreams, thus decreasing the amount of health problems people experience due to lead.

Lead causes damage to neurons within the human body by stimulating calcium, which is used by neurons to carry electric impulses. When lead stimulates calcium, the body thinks it is sending impulses through neurons affected by lead, but instead of calcium passing the charge through, the lead, in the place of the calcium, blocks the charge, keeping the neuron from firing. The receptor blocked by lead is known as the N-methyl-D-aspartate receptor (Brochin et al. 2008).

Damage to bones is caused by lead effectively blocking calcium from being absorbed by bones. Calcium is a major component in bones and is what gives them their hardness. This means the bones can not use the calcium to build themselves up, making them weaker and slower to repair damage (Brochin et al. 2008).

Additionally, within cells lead blocks hormones from leaving. This reduces the ability of cells to talk to one another. Calcium 2+ ions are the primary means of opening the cell membrane to allow hormones to leave. Lead blocks the calcium, preventing the hormones from leaving the cell. This is a serious issue given that hormones are how cells communicate to help maintain homeostasis within the body (U.S., Environmental Protection Agency, 2017).

A common theme, as shown above, with in the way lead impacts the human body internally is that it interferes with calcium. This is because lead and calcium bind to the same receptors within the body. Consequently, the more calcium someone has in their body, the less of an effect lead will have on them. However, the ideal solution would be to reduce lead exposure.

Toluene and 2-Phenylethanol were found to have the highest octane ratings. Therefore, they are the two primary types of fuel that should move onto further testing. If in additional testing both Toluene and 2-Phenylethanol are found to have properties that prevent them from being suitable Avgas replacements, the other fuels studied can also be taken into additional testing. After 2-Phenylethanol, Ethanol would be the next fuel to be tested, then Superbutol.

Sources of Error

A possible source of error was in the reporting of RON values. To help prevent this, data for each fuel was obtained from a minimum of three sources per fuel. The reported octane ratings all were within 1 of the mean octane rating for the given fuel. The one exception to this was

Toluene. Its reported octane ratings were at most 2 away from the mean, the largest difference of all the fuels.

The reason for different octane ratings is that there wasn't a standard system for measuring the RON values used by all the papers. The methods were similar, but not exactly the same. This could have led to slightly different reported RON values.

Limitations

It is important to note that there may be other fuel types that were not tested in this study that might satisfy the octane requirement. There are hundreds of fuel types already produced and more being designed. The study was limited by two factors in regard to addressing more fuel types. One was scope, there was only so many fuel types that could be investigated in the time available for the study. A second factor was the availability of information. A lot of high performance fuels are being produced by large companies such as Shell or Chevron. These companies do not openly give out information about these fuel types. Therefore, many fuels that could have been promising candidates to replace Avgas could not be considered because of a lack of publicly available information. There are also many fuels that there is not enough information on for this study due to a lack of research on those fuels.

Conclusions

The results of the study indicate that all the proposed fuels: 2-Phenylethanol, Ethanol, Superbutol, and Toluene meet the octane requirement to replace Avgas. This confirms my alternative hypothesis. Since they all meet the requirement, the two fuels with the highest octane ratings will be selected must be researched further. Toluene and 2-Phenylethanol had the highest octane ratings of 118 and 110.33 respectively, making them the most promising fuels to move onto further testing to see if they can replace Avgas.

Further work

All the proposed fuels had sufficient octane ratings to replace Avgas; The top two fuels, Toluene and 2-Phenylethanol, should move on to further testing to determine the best alternative to Avgas. While this study found the fuels to have sufficient octane ratings, there are other factors that need to be considered if they are to replace Avgas.

First, the fuels would need to be tested in aircraft engines under non-regulated conditions. Since the fuels were tested inside a lab to determine their octane ratings, they will need to be run in a more complex environment to see how they interact with the engine system, determine how performance is affected, and if the fuels perform sufficiently in those conditions.

Secondly, if the fuels pass outdoor conditions testing, they would need to be tested under extreme conditions. One extreme condition is at high altitude. At higher altitudes the air pressure is less than at ground level. Therefore the fuel-air mixture in the engine is greater. The fuels would need to be tested to see if they maintain satisfactory power under low pressure conditions. Another extreme condition is cold weather. In cold weather the fuels might freeze. Even just sitting in the fuel tanks on the ground, if the fuel freezes it could expand and blow up the fuel lines and tanks. Additionally, in flight the fuel would be more viscous, reducing fuel flow. If fuel flow is too low the engine would be starved of fuel and stop working. The fuels would need to have a low freezing point in order to not compromise planes stuck in cold weather. An additive could probably be used to decrease the fuels freezing point.

Thirdly, any additional fuel properties that might hinder their ability to perform would need to be examined. If, for example, one of the fuels dissolves plastic tubing, it could not be used since it could dissolve some of the fuel lines. Fuels could have any number of hidden characteristics that could interfere with engine performance which would need to be taken into account.

Fourth, lead helps to lubricate some engine components. These fuels might be able to do that, but if not, something would need to be done to serve that purpose. The fuels might possess lubricating properties, but probably would not do this on their own. The best solution to this problem would be to use an additive that serves this purpose.

Lastly, this study did not account for fuel cost. If multiple fuels are ultimately found to be suitable to replace Avgas, the cost of the different fuels might prove to be a significant factor. As the cost of flying is already high, pilots would prefer to pay less to fly. Especially if there is an increase in fuel performance for either fuel. If multiple fuels meet the requirements to replace Avgas, the lower costing fuel would be a better alternative in this respect, even if it has lower performance.

Another important note is that the fuels were considered without any additives. If a fuel has a negative characteristic or some property that does not meet the necessary threshold, an additive might be able to improve that property to a satisfactory level. This however, would increase the cost of fuel production, but should not be discounted as an idea if none of the fuels pass further testing.

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