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# Advancements and Challenges in the Search for Lead-Free Aviation Fuel: A Review

1st Muhammad Nur Cahyo Hidayat Nasrullah
*Department of Mechanical Engineering*
*Jember University*
Jember, Indonesia
mncahyohn@gmail.com

2nd Muh Nurkoyim Kustanto*
*Department of Mechanical Engineering*
*Jember University*
Jember, Indonesia
nurkoyin@unej.ac.id*

3rd Mahros Darsin
*Department of Mechanical Engineering*
*Jember University*
Jember, Indonesia
mahros.teknik@unej.ac.id

4th Nasrul Ilminnafik
*Department of Mechanical Engineering*
*Jember University*
Jember, Indonesia
nasrul.teknik@unej.ac.id

5th Skriptyan Noor Hidayatullah Syuhri
*Department of Mechanical Engineering*
*Jember University*
Jember, Indonesia
skriptyan.syuhri@unej.ac.id

***Abstract*— The quest for lead-free aviation fuel has spurred advances in technology and environmental sustainability. This article presents a concise overview of aviation fuel evolution, primarily focusing on the search for alternatives to traditional-led Aviation Gasoline (AVGAS). Since the inaugural flight by the Wright brothers in 1903, avgas became integral to piston-engine aircraft, albeit with environmental concerns due to its lead content. Consequently, extensive research has pursued cleaner fuel options to mitigate lead emissions' environmental and health hazards. Numerous studies have explored potential substitutes for avgas, including mogas, alcohol-based additives, and fuel blends, aiming to maintain aircraft performance while reducing or eliminating lead content. Recent investigations have assessed the effects of different fuel processes on aircraft performance and emissions. High-octane mogas (RON 98) has emerged as a promising alternative to replace leaded avgas, showcasing its potential as a viable solution. Despite progress, further research is essential. Pursuing cleaner aviation fuel requires balancing performance optimization and environmental sustainability. Continued exploration and experimentation are crucial to identifying optimal solutions meeting aviation standards while ensuring a safer, greener future for air travel.***

***Keywords*—AVGAS 100 LL, unleaded avgas, piston engine aircraft, Cessna 172, article review**

## I. INTRODUCTION

The endless blue sky has long been a pathway for humans' dreams to fly to distant places and reach peaks that have never been reached. The history of aviation records the beginning of the encounter between humans and the sky, starting with the flight that changed the world, namely when the Wright brothers flew their plane in 1903 [1]. However, this dream of flight brings joy and wonder and poses significant challenges regarding the environmental impact of using conventional aircraft fuel [2]. In this case, especially fuels that contain lead [3].

As is well known, aviation fuel technology has developed with the most significant advances since the historic flight of the Wright brothers in 1903, which occurred around World War II. The event that changed this paradigm was the invention of the gas turbine engine or "turbojet." The fuel for this new engine developed from Aviation Gasoline (Avgas) fuel technology to become the fuel now known as aviation turbine or avtur [4]. Aircraft engine types are divided into jet and piston engines [5]. Jet engines or gas turbine engines are commercial aircraft widely used by airlines to carry passengers and cargo in large quantities over very long distances [6]. Meanwhile, airplanes with piston engines or reciprocating are fueled by avgas used in general aviation, such as for flight training, or are also often used in the agricultural sector [7].

Problems arise when using avgas fuel in piston engine aircraft. Despite its toxicity impact, all known aviation fuel brands use TEL (Tetra Ethyl Lead) as an anti-knocking additive [8]. It is because one of the leading indicators of engine piston fuel quality is its ability to resist knocking [9]. Such an ideal fuel is characterized by a high octane rating [10], [11]. However, with the positive effects on machine performance, there are adverse effects on the environment and human health [12]. In adults, a certain amount of lead in the blood can be a cancer agent [13]. Likewise, in children, the avgas content in the body can cause a decrease in IQ and even academic problems [3], [13].

However, research on aviation fuel carried out by most researchers can be categorized into two. Research regarding Aviation Gasoline (Avgas) discusses a lot about unleaded aviation gasoline [9], [14]–[17]. Meanwhile, jet engine fuel mainly discusses renewable aviation fuel [18]–[21]. The search for unleaded avgas was carried out several decades ago [22]. In 1982, an experiment was carried out to fly a Cessna 150-type aircraft to reduce the use of Avgas fuel [23]. Then, in order to continue the search for unleaded avgas fuel, the Federal Aviation Administration (FAA) appointed the Piston Aircraft Fuel Initiative (PAFI) as an organization that focuses on finding alternative aircraft fuels without the use of lead as an additive which is currently used in 100 LL Avgas [24]. Meanwhile, for its application in aviation, the FAA permits piston engine aircraft users to use mogas as a mixture of avgas fuel but must first go through approval of the supplement type certificate (STC) issued by the FAA [25] It is done solely to reduce the use of lead in 100 LL avgas fuel.

From the description above, it is deemed essential to write an article that aims to comprehensively review the latest developments in the development of unleaded aviation fuel. Starting from the search for cleaner fuels to experiments and implementation on aircraft. By investigating the journey of the development of unleaded aviation fuel, this article can provide readers with comprehensive insight into the evolution that has occurred and the future direction of the aviation industry in its efforts towards skies free from lead emissions.

## II. HISTORY OF AVGAS

Aviation Gasoline (Avgas) development began in the early 1900s, more than 100 years ago, while the history of unleaded Avgas stretches back around 80 years [26]. Before the mid-20th century, aviation fuel was still combined with conventional gasoline. Therefore, aircraft still use conventional motor vehicle fuel. In 1903, the Wright brothers made the first airplane to carry passengers. This aircraft uses motor vehicle fuel with an octane number of less than 40. From 1903 to 1918, motor vehicle gasoline with an octane number of around 40 to 70 was used as the primary fuel in the aviation industry [26].

Avgas, also known as aviation gasoline, is used in piston engine aircraft, in contrast to aircraft using turbo-jet or turbo-prop engines, which use aviation fuel. However, the performance of this fuel is similar to conventional gasoline. However, there are significant differences. Avgas tend to be less volatile, has a lower freezing point, and a higher octane number than conventional gasoline. Some common additives mixed into Avgas include alkyl lead-based anti-knock additives, metal deactivators, colorants, oxidation inhibitors, anti-corrosion, anti-freeze, and static inhibitors [27].

Aviation Gasoline (AVGAS) standards are a fundamental part of the safety of piston-engine aircraft. Approximately 230,000 aircraft worldwide rely on the AVGAS 100 low-lead (100LL) in their operations [28]. Avgas, with grades 100 and 100LL, has an octane rating of 100 and is the most widely used. These two grades contain approximately 1.0 and 0.5 grams per liter of Thetra Ethyl Lead. A much higher amount compared to today's automotive gasoline. 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 United States. The second number reflects the octane rating of the fuel tested to "aviation rich" standards, which attempt to mimic supercharged conditions with a rich mixture, high temperature, and high manifold pressure. For example, 100/130 avgas have an octane rating of 100 on the "lean" setting, usually used for cruising, and 130 on the "rich" setting, which is used for takeoff and full power conditions [27].

## III. LEAD EMISSION ASSOCIATED WITH EXTENDED EXPOSURE TO AVIATION GASOLINE OPERATIONAL

Before 1970, because there was no information regarding the side effects of Tetra Ethyl Lead as an additive, TEL consumption in fuel was considered normal. From 1970 to 1980, the impact of lead emissions received increasing attention. Finally, the use of lead in all industries began to be banned in 1996 [29]. However, using lead in piston aircraft fuel is still challenging, even though some potential dangers must be addressed.

The study by Park et al. [30] revealed that emissions from AVGAS could increase Blood Lead Levels (BLL) in aircraft maintenance crews. The study subjects had an average geometric BLL of 3.74 µg/dL, which may be higher than adults in general in Korea. This finding is almost similar to previous research conducted by Kim et al. [31] and Lee et al. [32]. However, this level is still lower than the 40 µg/100 g guideline recommended by the Occupational Safety and Health Administration (OSHA). The results of this investigation indicate that increased BLL levels can occur in aircraft maintenance crews who work for long hours within 200 meters of the runway. Overall, the results of this study and previous research suggest that long-term stays or activities near air facilities should be limited, given that lead poses known health risks.

Apart from that, the study conducted by Atluntas et al. [33] found that the number of landings and take-offs at airports using aircraft with lead fuel could increase the exposure value in that area. It is due to the high amount of water traffic in the area. So, to normalize it, it is recommended to use unleaded fuel.

## IV. BEGINNING OF UNLEADED AVGAS

It all started with the Clean Air Act Amendments in 1990, which called for the use of lead in all gasoline motor fuel to be eliminated by the end of 1995 [34]. Even though this regulation is not binding regarding lead in aircraft fuel, the Federal Aviation Administration (FAA) is still developing unleaded avgas fuel. In response to requests from Congress, the FAA has initiated research to develop unleaded aviation fuel. However, research conducted by the FAA still needs to be improved with feasibility certification based on vapor lock behavior and engine performance [35].

Previously, in 1970, the Experimental Aircraft Association began flight feasibility trials of the Cessna 150 aircraft using conventional unleaded gasoline. This fuel offers several advantages: lower purchasing and maintenance costs than 100LL avgas and is readily available nationwide. In 1979, an official engineering program was undertaken to flight test the Cessna 150 aircraft to check the safety of the aircraft using unleaded automobile gasoline under such adapted conditions. Then, finally, around 1983, due to availability and cost problems in providing aviation fuel to users. Moreover, due to high maintenance costs and decreased reliability when using aviation fuel with 100 LL octane in aircraft engines with a minimum of 80 octane. Zeisloft, via the Experimental Aircraft Association, reports flight tests to determine aircraft safety and compliance with Federal Aviation Regulations when using conventional vehicle gasoline [36]. The trials were conducted using a Cessna 150 aircraft with a 100 hp Teledyne Continental Motors engine. Actual footage of the tested aircraft is displayed in Figure 1. Based on this test, the FAA has approved using unleaded automotive gasoline in all Cessna 150 aircraft using the Teledyne Continental Motors 100 hp engine. No changes are required to the airframe, engine, or aircraft operations.

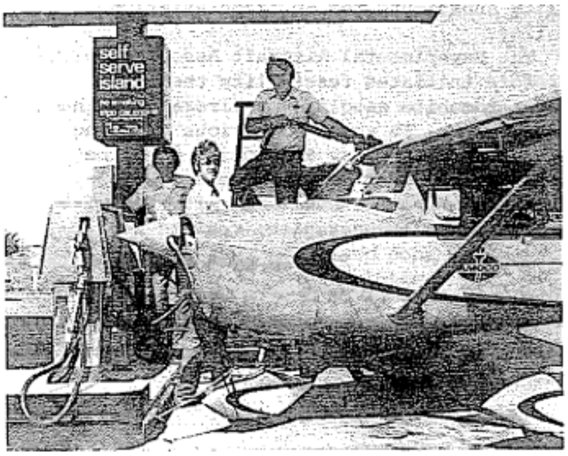


Fig. 1. Real footage of tested aircraft on Zeisloft et al [36].

Furthermore, in 1988, the FAA, represented by Ferrara et al. [37], conducted experiments to see how changes in air pressure affect aircraft fuel. They tested various types of unleaded gasoline at various air pressures and noted how this affected how the plane operated and the properties of the fuel. They tried varying the composition of the fuel, the way the plane was set up, and the fuel temperature when it was put into the plane's tanks to see how much influence these variables had on how the plane worked. The experiment was carried out by heating fresh fuel in a closed container, bringing it to a certain pressure height, and then filling it into the aircraft tank. The aircraft was then flown for an accumulated 50 flight hours using test fuel, and changes in aircraft performance were recorded. A photo of the original aircraft used for testing is shown in Figure 1. The experimental results show that fuel containing butane tends to have more frequent vapor lock problems than fuel containing pentane. However, fuels containing pentane tend to change more slowly, while vapor lock problems last longer. Fuel volatility is measured using the Reid Vapor Pressure method. Changes in fuel volatility tend to follow the same pattern as changes in aircraft performance, with butane fuel changing more rapidly than pentane fuel. The transition of hot fuel causes the loss of more volatile components; as a result, fuel at 70 degrees Fahrenheit exhibits more severe vapor lock problems than fuel at 90 or 110 degrees Fahrenheit. Aircraft configuration does not influence these trends, although vapor lock will occur at different Reid Vapor Pressures depending on aircraft configuration. In addition, experiments were conducted to evaluate aircraft fuel certification procedures. The results showed that heating the fuel to 115 degrees Fahrenheit significantly reduced the likelihood of vapor lock. In tests using Methyl Tertiary Butyl Ether (MTBE) as test fuel, no problems were found except for paint incompatibility and swelling of the Viton O-ring. No other problems, such as valve shrinkage, were found. Testing of oxygenated fuels such as alcohol/gasoline and MTBE/gasoline blends showed a similar reduction in volatility after 48 hours of storage at 110 degrees Fahrenheit.

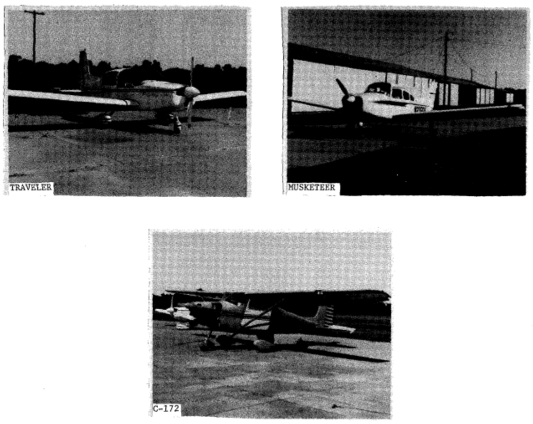


Fig. 2. Real footage of tested aircraft on Ferrara et al [37].

## V. RECENT RESEARCH ON UNLEADED AVGAS

Recent research has resulted in developing and evaluating various types of unleaded aviation fuel aimed at replacing Avgas 100LL. UL82 and UL87, regulated according to ASTM standard D6227, are intended for engines with low compression ratios. UL91 and UL94, which meet ASTM D7547 standards, have been widely researched and accepted as potential replacements for more than 90% of the aviation fleet currently using Avgas 100LL. Additionally, ongoing studies and development involving UL100 and UL102, designed to meet ASTM D7960 and ASTM D7719 specifications, show potential as replacements for currently standard lead-based aviation gasoline [38].

However, before going through all that, much research has been conducted to find alternatives to unleaded fuel. Starting from replacing Avgas with kerosene [39] to the addition of alcohol additives in the form of n-butanol [40], n-pentanol [41], or ethanol [42]. Therefore, in most of the research on aviation gasoline fuel, the main aim is to develop unleaded fuel, and it is estimated that it will take until 2030 in the adjustment process to stop the use of lead in aviation gasoline completely [38].

Apart from adding these additives, several researchers are looking for uses for unleaded avgas fuel, or at least reducing its use has several methods, including those carried out by Gökmen et al. [43], which discusses mixing by volume worth 5% avgas 100 LL and 95% mogas with an octane number of 95. Then, a test was carried out using a direct injection engine, and the test equipment setup is shown in Figure 3. The results briefly explain that an increase in engine speed increases torque and engine power on all test fuels, including Avgas. However, the exhaust gas and engine oil temperatures increase when using Avgas and increasing engine speed. Although noise levels increased with increasing engine speed on all test fuels, using Avgas reduced noise levels. Specifically, specific fuel consumption decreases for all fuels up to 3000 rpm but increases afterward. On the other hand, the use of Avgas reduces specific fuel consumption.

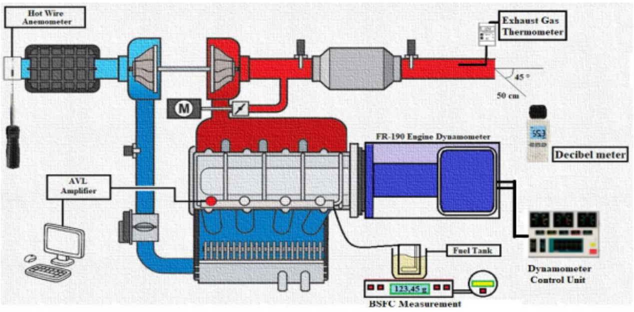


Fig. 3. Schematic diagrams Gökmen et al [43].

Kumar et al. [25] observed the relative detonation index of 14 types of fuel consisting of Avgas, Mogas, and a mixture of the two, using a Lycoming O-320 engine, which is a powerplant used in one of the piston engine aircraft, the research scheme is shown in Figure 4. In comparison, the data for 14 types of materials, including the fuel used, is shown in Figure 5. It is known that the test results using RON 98 fuel tend to be accepted as a replacement fuel for Avgas compared to several types of fuel that have been tested.

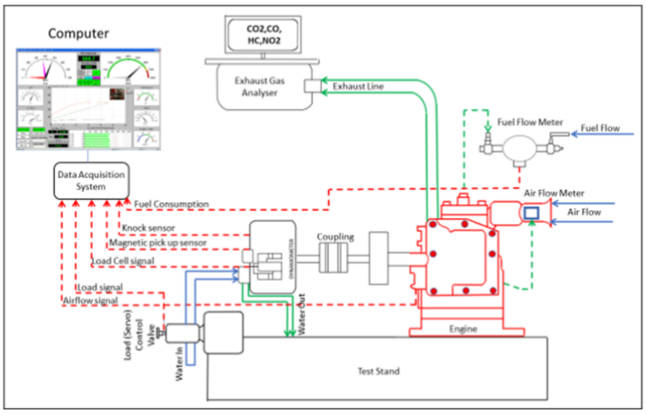
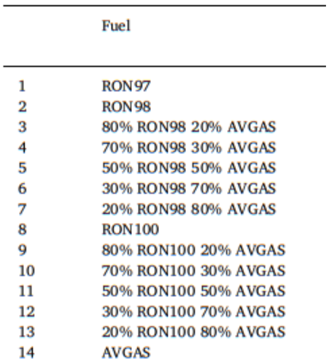


Fig. 4. Engine test bed's schematic diagram [25].

TABLE I. FUEL STUDIES ON THE RESEARCH [25].



| | Fuel |
|---|---|
| 1 | RON97 |
| 2 | RON98 |
| 3 | 80% RON98 20% AVGAS |
| 4 | 70% RON98 30% AVGAS |
| 5 | 50% RON98 50% AVGAS |
| 6 | 30% RON98 70% AVGAS |
| 7 | 20% RON98 80% AVGAS |
| 8 | RON100 |
| 9 | 80% RON100 20% AVGAS |
| 10 | 70% RON100 30% AVGAS |
| 11 | 50% RON100 50% AVGAS |
| 12 | 30% RON100 70% AVGAS |
| 13 | 20% RON100 80% AVGAS |
| 14 | AVGAS |

In their research, Manickam et al. [15] tried to find alternative fuels for piston-engine aircraft with the minimum lead. Tests were carried out using Avgas mogas fuel and mixing the two to determine the tendency for vapor lock to occur. The test equipment used is a Lycoming O-320-D3G-type piston aircraft engine. The finding that needs to be underlined is that mogas with RON 98 can become one of the fuels with the best potential in preventing vapor lock. The structure of the testing tool in this research is shown in Figure 6.

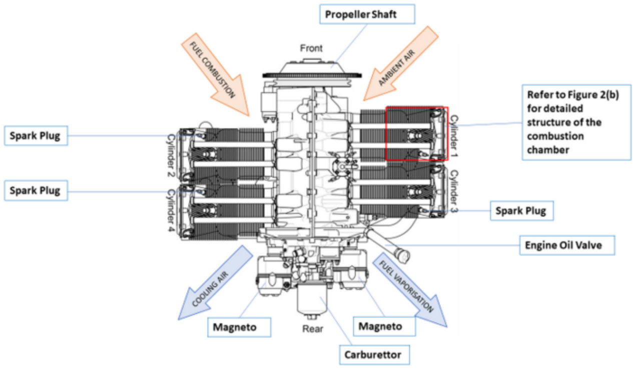


Fig. 5. Schematic diagrams Manickam et al [15].

Sulung et al. [44] discuss the flame color characteristics of the Bunsen burner combustion test of a mixture of Avgas 100 LL and Pertamax. The greater the Pertamax content in 100 LL avgas causes a tendency towards yellow in the flame color. It is supported by research by Lou et al. [45]. which states that the flame's color can indicate soot formation during the combustion process. The image of tests carried out by Sulung et al. is shown in Figure 6.

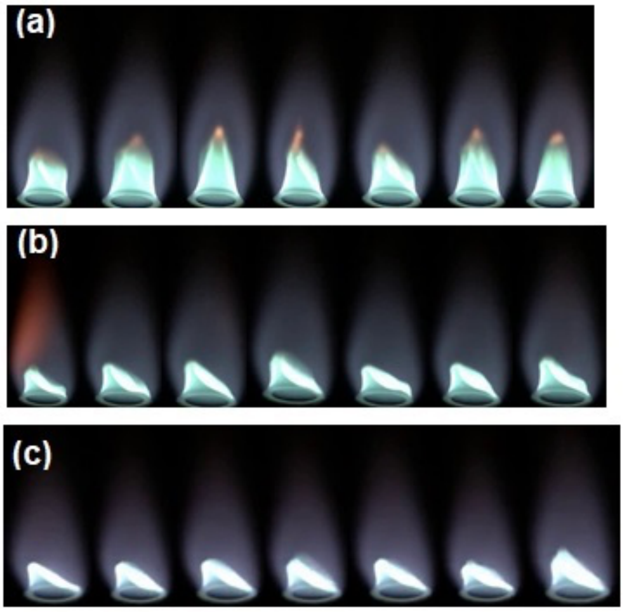


Fig. 6. a) 50% avgas, 9 milliliters/hours. b) 75% avgas, 9 milliliters/hours. c) 100% avgas, 9 milliliters/hours

## VI. CONCLUSION

From the previous discussion, efforts to replace Avgas with alternative unleaded fuel are essential in protecting the environment and human health. Although there has been some progress in developing alternative fuels, further research and experimentation are still needed to find optimal solutions with good performance, widespread availability, and minimal environmental and human health effects.

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