Collective Knowledge on Aviation Gasolines

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Collective Knowledge on Aviation Gasolines

In partial fulfillment of the requirements for the Degree of Master of Science in Technology

A Directed Project Submitted to the Faculty of Purdue University

by

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# Table of Contents

DEDICATION .................................................................................................................. iii
ABSTRACT ...................................................................................................................... iv
INTRODUCTION ............................................................................................................. 1
LITERATURE REVIEW ................................................................................................. 6
METHODOLOGY ............................................................................................................. 14
DATA AND RESULTS .................................................................................................... 17
CONCLUSIONS AND RECOMMENDATIONS ................................................................. 18
REFERENCES ................................................................................................................. 20
APPENDIX # 1. COPY OF TEXTBOOK CREATED ........................................................... 21
  Chapter # 1 - The History of Aviation Gasoline ............................................................... 21
  Chapter # 2 - ASTM D910 - The Backbone of Aviation Gasoline ................................. 39
  Chapter # 3 - AGE85 - Aviation Grade E85 Ethanol as an Alternative to 100LL .......... 63
  Chapter # 4 - Hjelmco Oil – Unleaded Alternatives ...................................................... 74
  Chapter # 5 - Automobile Fuel for Airplanes ............................................................... 83
  Chapter # 6 - 82UL Aviation Gasoline ......................................................................... 98
  Chapter # 7 - SwiftFuel – Sustainable, renewable, synthetic ......................................... 106
  Chapter # 8 - 100VLL Aviation Gasoline ..................................................................... 114
  Chapter # 9 - Aviation Fuels Certification ................................................................... 120
  Chapter #10 - Miscellaneous Aviation Gasolines ......................................................... 128
SPECIFICATION APPENDIX ......................................................................................... 135
DEDICATION

This work would not have been possible without those people who have influenced my life and always believed in me. This work is dedicated to the following individuals:

To my graduate committee: Professor Mark Thom and Professor David Stanley. Without your willingness to take on my graduate work and expert guidance, this work would not be possible.

To John and Mary Rusek: Who were willing to entrust their faith in my enthusiasm to learn new things. Without their guidance and encouragement, I would have never ventured in to aviation fuel engineering.

To my Parents, Ron and Sherry Ziulkowski: Without their love, support, and guidance; my academic achievements would not have been possible.

Most of all, this work is dedicated to my wife, Susan Ziulkowski. Her continual encouragement to follow my dreams is the catalyst for my success. It is with her support that I have learned; even the largest task is possible, one step at a time.
ABSTRACT

Ziulkowski, J., Purdue University, June, 2011 Collective Knowledge on Aviation Gasolines.
Committee Chair: Professor James M. Thom.

The problem being faced is that there exists little data in a collective location surrounding aviation gasolines. In recent years it has been observed that most involved in the general aviation community are unaware of efforts and solutions underway to replace current leaded aviation gasoline. The point of this research was to collect and distill the history of aviation gasoline, some alternatives and their shortcomings, and indicate where the industry is headed. This information is divided into ten different chapters which is compiled into a book for students in the Purdue Aviation Technology Department. Following successful completion as a graduate project, the information will also be compiled in a formal textbook.
SECTION 1. INTRODUCTION

The United States has been at the forefront of aviation during the first one hundred years of powered flight. With more than 6,000 small and large airports, the United States is number one on the world stage of general aviation. With rising fuel costs being a problem in all industries, users of 100 low-leaded gasoline in general aviation have felt the hardest blow of all with fuel prices reaching of $8 per gallon in some places of the United States. Currently, there are only a handful of refineries producing 100 low lead (AvGas). AvGas is the only gasoline in the US to still be allowed to contain tetraethyl lead (TEL), resulting in the inability to transport and distribute the fuel to airports as easily as automobile gasoline is distributed to gas stations. The Environmental Protection Agency (EPA) has slated to cease TEL additives in AvGas by January of 2017 (Passavant, 2009).

1.1. Problem Examined

Students in aviation studies have substantial knowledge pertaining to aviation operations, and have a keen interest in alternative fuel and the development of possible replacements. Unfortunately, there exists no single source where one can learn the basic common knowledge of how aviation fuel got to where it is today in aviation fuels, and where other potential options for replacement have fallen short. Because most of aviation is delineated by the regulatory process, usually controlled by the FAA, most students, and most aviation professionals, do not understand the certification processes on which the FAA bases its regulatory standards. With regard to fuels, and the creation of new fuels, it is impossible for the aviation student, the aviation student researcher, or the aviation professional, to undertake developmental research and new product certification without a detailed understanding of this materials certification process. The problem then becomes that there is no text for interested
students to read for them to understand the fundamentals of the fuel spec certification process, a survey of how leaded fuels have come to exist, and the options for replacing leaded fuels.

1.2. **Scope**

This project was designed to educate those who are more than likely involved in testing and proving alternative fuels viability and or using those future fuels in the near future. The intended audience are university-level students (of a freshman or sophomore level), interested aviation professionals as well as policy makers, and representatives in government and advocacy groups.

1.3. **Significance**

Without background understanding of aviation fuels, the development process, and the certification process, aviation researchers cannot appropriately evaluate alternative fuels; thereby, negatively impacting the industry.

Now more than ever the correct political climate exists for alternatives to 100LL. This is evidenced by the EPA and FAA openly searching for alternatives to TEL and OEM’s willing to participate in both private and university studies to find an alternative fuel. In response to the industries demand for testing and proving of fuels, The National Test Facility for Fuels and Propulsion (NaTeF) and Purdue have aligned themselves to be on the forefront of testing, proving, and method development. The outcomes affects the vast group of nearly 415,000 pilots and aircraft owners in the United States, and nearly triple that amount of people who benefit directly or indirectly from general aviation yearly.
Without TEL, spark-ignition, piston engine aircraft are unable to meet minimum performance standards set forth by the Federal Aviation Administration (FAA); effectively rendering the light general aviation aircraft un-airworthy or non functional. 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 freezing aloft. Also, with ethanol an aircraft owner would have to modify the engine solely to burn ethanol; due to its disparate air to fuel ratio, current modifications can cost owners dearly in cost and time to make the necessary repairs. If immediate action is not taken to come up with an alternative fuel for AvGas, general aviation in the United States is likely to cease to operate.

If replacement fuels are tested and proven, the general aviation community can continue to thrive for decades to come with a renewable resource that is cleaner for the environment. In order for this testing and proving to happen; however, those in the general aviation community must be willing to embrace the future. This nonetheless can be hampered if a lack of understanding exists. If a replacement fuel is not tested, proven, and certified, general aviation is likely to grind to a halt, with no viable replacement for 100 low lead gasoline (100LL) after the EPA no longer allows TEL to be used as a fuel additive.

With Purdue’s NaTeF gearing-up to support the development of alternative fuels, it is imperative that a collective body of knowledge be compiled and used by those that would be involved in NaTeF’s operations. The NaTeF researchers have expressed a desire for the kind of summary developed in this study for use in educating student researchers on the fundamentals of leaded fuel development and certification.
1.4. Definitions

100LL – 100 octane low leaded aviation gasoline for piston engines.

AGE-85 – a mixture of 85% ethanol and 15% gasoline used in aircraft.

AOPA – Aircraft Owners and Pilots Association

ASTM International – American Society for Testing Materials, the group who publishes standards.

Avgas – Aviation gasoline

BOCLE– Ball-on-Cylinder Lubricity Evaluator (ASTM D5001)

CFR (Combustion Fuels Research) engine- A special lab research engine which has the capability to vary fuel mixtures, valve timing, ignition timing, cylinder displacement, and cylinder compression ratios for the purpose of evaluating fuel detonation characteristics.

DoT – Department of Transportation

E-85 – a mixture of 85% ethanol and 15% 87 octane gasoline used in automobiles.

EPA – The United States Environmental Protection Agency

FAA – Federal Aviation Administration, the governing body of aviation in the US.

GA – General Aviation

lean (mixture) – referring to the air to fuel mixture in an internal combustion engine, this condition is referring to less fuel in the mixture than air, just enough to keep the engine running.

NaTeF - The National Test Facility for Fuels and Propulsion

OEM – Original Equipment Manufacturer

TEL – tetra-ethyl lead

WPAFB – Wright-Patterson Air Force Base
1.5. Assumptions

The project has been developed according to the following assumptions. The fuel of interest is limited to spark-ignition aviation gasoline used in piston powered general aviation aircraft. The information that has been gathered by over five years of individual work in this industry is fully verified by independent laboratories, the ASTM, or the FAA. Most Purdue aviation students do not have above a basic understanding of the origins of current (100LL) aviation gasoline.

1.6. Limitations

This project takes a look into the cooperation that exists between ASTM and the FAA of any new fuel to be examined; however, since there is no clear and defined method for final certification of any replacement for 100LL, the information in this study is based on industry stakeholder guidance. Another limitation of the research is that not all information can be presented in great detail. Some of the alternative fuels mentioned have corresponding voluminous research reports that have been submitted to ASTM and the FAA. Summaries are presented with the appropriate reports listed, if further research is needed. Because of this need to condense hundreds of pages of historical and technical information into a summary for new researchers, there is going to be some loss of highly technical detail, which can only be gained by reading the original documents.

1.7. Delimitations

This project does not examine anything outside of the aviation spark-ignition gasoline arena. Since the FAA has confirmed that fuel certification goes through ASTM exclusively, only those fuels past and present which use this process will be examined. Finally, this project was limited to the research,
compilation, and deliverance of: a text with ten chapters each covering a different aspect of aviation gasoline.

SECTION 2. LITERATURE REVIEW

An appropriate place to survey the current market of renewable fuels was through a review of the available literature. At the time of the research there was significant attention given to renewable and bio-derived fuels. However, this information was not applicable to aviation, let alone aviation gasoline. It would have been inappropriate to pursue this project if the requisite body of knowledge had already been amassed through another medium or vehicle, such as scholastic journals. The following describes how the data, largely available as esoteric industry documents were compiled and contrasted for one of the more in-depth chapters in the text, Chapter # 1 - The History of Aviation Gasoline.

2.1. Methodology of the literature review using Chapter 1 as an example

When writing this chapter, the first place to begin searching was not found in a text or industry journal; rather research began right at the source, the experts. Due to personal involvement with the ASTM International, I was involved on a task force which undertook the writing of a document detailing the history of avgas. This document served as the origin of this research as it was probably the most complete due to the input of multiple industry experts, whose companies were responsible for the shaping of avgas since its inception. The logical place to start was with the Wright Brother’s first powered flight. There was not a lot known about the first years of avgas, so little in fact, that most of the experts that comprised the 50 + member task force had no record of composition dating farther back than 1917. Further attempts to dig into the earliest years of avgas were met with a lack of information and data. This chapter begins by explaining that the ASTM task force document that was created was a
painsstaking process, since the participating companies are bound by the Sherman Anti-Trust Act. A short explanation was provided on the significance of the Sherman Act of 1890 from Encyclopedia Brittanica.

The bulk of the chapter detailed the beginning of bifurcation between autofuel and avgas. A few examples of specialty avgas are given and a quote was inserted from Alisdair Clark of British Petroleum to demonstrate the reasons for creating specialty aviation fuels, pointing to safety of flight as the penultimate rationale. The chapter then discussed the discovery of TEL. A search of the online encyclopedias yielded when TEL was first discovered, but further explained that it was not until the late 1920’s that detailed research on its effects on fuel was conducted. A quote from the National Inventors Hall of Fame frames the trial and error method employed during discovery. This section mentions the formation of the CFR group as a predecessor to ASTM.

The chronology continued and began to explore the early uses of lead additives in Army testing. Another quote highlighted some of the failed early tests with TEL (Clark, 2007). This was contrasted by mentioning the Navy’s success with TEL, which produced the max TEL content for fuels in 1923. A segment of the ASTM report then was used to explain that fuel still did not exceed 100 MON. The next segment in the chapter details the early testing at WPAFB where the early work was done on a CFR engine. In personal communications with Alisdair Clark, he indicated that this was important to highlight to those wanting to understand aviation fuel development. This information was included, based on citations from his presentation in 2007. A brief explanation of MON and CFR engines was explained through the use of personal knowledge, industry expert explanation, and supporting documentation was cited. In personal communications with industry members it was pointed out that the history of development should include mention of the work in Europe that was occurring to develop TEL for fuels. The presentation from Clark and the ASTM report were used to explain the development in Europe as well as the discovery of iso-octane which led to the octane rating scale. This was shown through an
article from the ASTM periodical. Further excerpts from the ASTM report were used to demonstrate the ever-growing divide between avgas and auto fuel streams.

Personal conversations with ASTM industry experts were condensed into a few paragraphs surrounding the spool-up of leaded fuels with the advent of WWII (Clark, 2007). A few quotes were pulled from the task force report and interlaced with the verbal history from the experts. A study from the National Bureau of Mines surveyed avgas grades and showed the division of leaded and unleaded fuels in the beginning of the 1950’s, with the trend moving to all leaded. Much of the ASTM report was cited to show how the different grades evolved over time, with different limits being imposed in the ASTM specification over the decades.

The gradual transition to the sole fuel, 100LL, was shown with a quote from the EPA’s Glenn Passavant contrasted with a quote from the Clean Air Act. This issue was demonstrated through the graphical timeline of leaded avgas as crafted by the ASTM task force. This timeline was shown on page ten of the chapter and serves to demonstrate graphically the highlights of the chapter.

2.2. List of References

The following is an all inclusive list of references used for the compilation of the project text.

Each set of references is listed below, under its respective chapter.

Chapter # 1


Chapter #2


C. Sincock, personal communication. (2008, April 2). West Lafayette, IN.


Chapter # 3


Chapter # 4


Lars Hjelmberg, Personal Communication (15, December 2010). West Lafayette, IN.


Chapter # 5


Chapter # 6


Chapter # 7


**Chapter # 8**


**Chapter # 9**


**Chapter # 10**

SECTION 3. METHODOLOGY

The methodology for developing a summary of aviation gasoline involved four steps:

Step 1: Determine the requirements of the researchers regarding the scope and detail of such a primer for student education. In this step the level of detail needed, the amount of background desired, the number of fuels evaluated, and the certification processes desired to be explained was defined.

For this study the researchers of NaTeF expressed a need for a document that could be given to freshmen or sophomore college students in aviation, who had little or no technical or flight experience. The NaTeF researchers’ inputs were for the students to be able to read the primer and be able to get a sense for how fuel is controlled, who controls the fuel content and production, how lead in fuels came to be, what lead does in gasoline, and a history of attempts to eliminate lead from gasoline. It was requested that the primer be broken into 8 to 10 chapters.

Step 2: Survey the available industry literature, fuel specifications, historical documents, and glean information from personal contacts. The ASTM specifications, including historical documents were examined. Once a review of the written specifications was conducted, inquiries of personal contacts were made to fill in the blanks, regarding technical detail, any related political or non-technical information. These personal contacts were of the political and non-scientific background in fuel development and specification.

Step 3: Distill the gathered information and write the primer.

Step 4: Seek external review of the primer chapters for technical accuracy and overall quality. Industry experts in fuel chemistry, aviation fuels, aviation history, and fuel research were solicited for inputs on the draft primer. Changes and modifications to the primer were made per these experts’ recommendations.
Most of the methods employed for the completion of the project were developed and based on a working knowledge of the ASTM processes used for the qualifying fuels and past history of other proposed alternatives. As an ASTM member, the documents obtained to compile the research text were readily obtained. All of the industry documents, more specifically ASTM specifications, which were used or referenced in the text can be found in the Specification Appendix of this document.

3.1. Procedure

The overall nature of the investigation was a compilation and appropriate structure for dissemination of the knowledge. The end result of this project was a text with ten individual chapters. Each chapter covers an independent area of information. The chapters included: The history of aviation gasoline, development of ASTM D-910 fuel grades to include 100LL, AGE-85, Hjelmco 91/96, Autogas (MoGas) STC & the new ASTM D-6227, 82UL including both ETBE and MTBE, Swift UL102 (100SF), ASTM & FAA certification, ASTM D-910 grade 100VLL (very low lead), and finally other little known fuels to include; 93AKI, Foreign ‘B’ grades, and other foreign fuel grades. A separate list of references and citations accompanied each chapter. They can also be found in Section 2.2 of this document.

The text document that was created by the project is an appendix to this report. It can be found in Appendix # 1. It is also referenced in Section 4.

3.2. Industry Expert Overview

To ensure that the final text was as accurate as possible, the following industry members, who are considered subject matter experts, read and provided input to the current document:

- P.J. Catania – Aerospace Engineer and Formulation Expert – Swift Enterprises (ASTM Member)
3.3. Summary

The ten chapters were able to capture the essence of what the NaTeF researchers requested. It was able to be shown how lead came to exist in aviation gasoline and why it was used. Some technical discussion was presented on the effects of lead in the engines and why lead was so important. The development of the fuel specification process was detailed, and it was shown how a fuel becomes certified by the ASTM, and how the ASTM process works. That chapter was written to fill a gap in the understanding by the general population on the logic problems associated with fuel certifications, and the problems ASTM must consider when making changes to any fuel. The chapters also explained the advisory, as opposed to regulatory, role of the FAA in the process.

The chapters on new fuels development chronicle the efforts to reduce and replace lead in aviation gasoline over the past 30 years, and provide a summary of the industry’s common knowledge and common experience, which every fuels researcher should know.
Finally, this primer gathered the relevant references from which the primer was written. From these references a student of fuels development can now readily find and read the foundational documents for fuel development.

SECTION 4. DATA AND RESULTS

Because there was no quantitative data gathered and analyzed in the traditional sense of a graduate research program, the final project is the compiled text of ten chapters. This text is meant to be used as a compendium of knowledge used for teaching freshman and sophomore university students. The entire compilation can be found, in its final form, in Appendix # 1 of this document.

4.1. List of Chapters

- Chapter # 1 - The History of Aviation Gasoline
- Chapter # 2 - ASTM D910- The Backbone of Aviation Gasoline
- Chapter # 3 - AGE85 - Aviation Grade E85 Ethanol as an Alternative to 100LL
- Chapter # 4 - Hjelmco Oil – Unleaded Alternatives
- Chapter # 5 - Automobile Fuel for Airplanes
- Chapter # 6 - 82UL Aviation Gasoline
- Chapter # 7 - SwiftFuel – SUSTAINABLE. RENEWABLE. SYNTHETIC
- Chapter # 8 - Aviation Fuels Certification
- Chapter # 9 - 100VLL Aviation Gasoline
- Chapter # 10 – Miscellaneous Aviation Gasolines
SECTION 5. CONCLUSIONS AND RECOMMENDATIONS

This section draws conclusions from the conclusion of the project and production of the final text listed in Appendix # 1. Following the conclusions, recommendations for further areas of study and research, are discussed.

5.1. Conclusions

Now that it is complete, this text is an important compilation of information for those interested in alternative aviation gasoline. There currently is no single-source, simplified explanation for the novice interested in aviation fuel. This work allows a freshman or sophomore level university aviation student, of limited to no understanding of aviation gasoline to have a good cross section of the history, issues, alternatives and attempts to replace 100LL. From here a student can launch further research and have the foundational language and historical perspective of the industry experts doing gasoline research.

As the deadline to remove TEL from fuels rapidly approaches, this area of research has attracted the interest of the FAA’s top personnel in fuels research. The content covered in the final text is the most complete, accurate and up to date information in the industry. The average researcher would be unable to find or even locate this information. Now that it is compiled it can benefit those who wish to further understand the history of aviation gasoline or pursue research in alternative aviation fuels.

5.2. Recommendations

It is recommended that further work take place to more formalize the text created into a textbook. This would allow the text to be offered to a wider audience. It is further recommended that the text be augmented with multiple figures and photos augmenting the text. Finally, further
information is required about some of the proprietary formulations listed in chapter # 10. Due to the highly-secretive nature of these fuels, little information could be gleaned to accurately portray the listed fuels. Further information on testing and formulation would augment these sparse sections.

Chapter # 1

The History of Aviation Gasoline

The United States has been at the forefront of the aviation industry for the first one hundred years of human powered flight. With more than 6,000 small and large airports, the United States is number one on the world stage in general aviation. In order to study current aviation gasoline grades and future alternatives, it is important to first examine the history of where the fuel grades originated. This chapter gives a broad overview of the history of aviation gasoline.

Since the first powered human flight by Orville and Wilbur in 1903, spark-ignition gasoline has powered piston engine aircraft. It has not been until recently that the history of where we are today (100LL) has become clear through an exhaustive study of the documents and the specifications for aviation gasoline. The ASTM International subcommittee J of committee D02 (D02.J) took on this laborious task of examining the history of avgas in June of 2004. The DO2 committee has published a research report, with a timeline table (See Figure 1), which is considered by many in the industry to be the foremost reference in the timeline of avgas. This study is where the majority of the information for this chapter is drawn.

The ASTM D02 document was compiled from industry members who were members of D02.J. These members represented airframe manufacturers, oil companies and producers, distributors, engine manufacturers, and others. Prior to the convening of this task force, most of this information was known by each individual member as it pertained to their operation. This individual information once only populated the secret company records of oil companies’ libraries, and shelves in aviation manufacturer’s basements. During the process of compiling information regarding gasoline formulations,
improvements, and history the ASTM committee members, and especially the oil company representatives, had to remain mindful of the Sherman Antitrust Act of 1890. This act, “[...] made illegal all attempts to monopolize any part of trade or commerce in the U.S.” (Encyclopædia Britannica, Inc., 2011). Because of this, oil companies are unable to discuss anything that could be viewed or interpreted as collusion with other oil companies. Because of a history of collusion among oil companies in the late 19th and very early part of the 20th century, the United States government maintained a very close scrutiny of the exchange of information between oil companies, and users of petroleum products. So the Sherman Anti-Trust Act, deemed it illegal for very large, and very powerful companies, with a near monopolistic share of market, from meeting to discuss product secrets, pricing strategies, market strategies, or any other anti-competitive topics. The companies could meet publicly to discuss the creation and maintenance of quality control specifications, and to resolve product related problems which impact the public health and safety, among other things. However, under these strict ground rules, oil companies were willing to bring forth all of the information to the ASTM committee on what companies had done in the past regarding the development of aviation fuel.

Avgas began as minor improvements and subtle changes to regular automobile gasoline, or “mogas.” The first aviation gasoline types were comprised of crude oil distillates with a motor octane number of anywhere between 40 – 70 MON. (The topic of MON, or motor octane number is discussed in chapter 2) These early fuels were unleaded in nature, since tetra-ethyl lead (TEL) (the ingredient allowing for high octane fuel) was not even discovered until 1921 (ASTM D910 Task Force of D02.J.02, 2004). As aviation continued to evolve in the early years, it became apparent that regular automobile gasoline was not a good fit for aviation. Aviation engineers and oil companies began to realize that airplanes were operating in a much different environment than automobiles, where things like temperature and barometric pressure change and were not constant. Due to some of the early complications and limitations of the automobile fuel used in airplanes, in 1917 grade 8G1b “Aeroplane
Gasoline” was introduced (ASTM D910 Task Force of D02.J.02, 2004). This fuel was an, “Unleaded light hydrocarbon product specific to aviation introduced to increase flight safety/reliability” (Clark, 2007). The purpose of this new fuel was to create a type of gasoline that could go to high altitude without evaporating and vaporizing uncontrollably, and could withstand higher heat found on aircraft engines. This new fuel specification was also an early attempt at creating a consistency of heat, vaporization, and combustion characteristics that was not found in automobile gasoline. This was the point when aviation gasoline began to take a divergent path from standard automobile gasoline. From 1917 on, for nearly 100 years, aviation gasoline was always separated from the regular supply chain that carried all other gasoline types.

In 1918, a “Grade X” aviation gasoline and “Fighting Grade” of fuel were produced for aviation. These too were made from blended light hydrocarbons, known as straight run gasoline and unleaded (ASTM D910 Task Force of D02.J.02, 2004). Though TEL had first been discovered by a German chemist in 1854 (Kitman, 2000), it was not thought of as an anti-knock agent until sometime later. In 1921, Thomas Midgley, Jr., who was employed by General Motors, discovered that small amounts of TEL added to gasoline was able to stave off detonation and engine knock (Kitman, 2000). Engine knock was a phenomenon where the engine would make a loud pinging or knocking sound as it ran at high power. It was found that when engines displayed this knocking sound, internal damage and failure of parts in the combustion chamber were often found. In some cases catastrophic engine failures would occur. A small account of Midgley’s work shows how he ‘discovered’ TEL for use in gasolines, “Midgley soon uncovered that contrary to popular belief, knock was the result of a fuel failure, not an engine failure. A trial and error search commenced to find a fuel additive that would reduce the temperature and pressure within the cylinder to suppress the knock. In December 1921, an engine test was run with a small amount of tetraethyl lead, completely eliminating knock” (National Inventors Hall of Fame, 2002). What Midgley had discovered was that it was an uncontrolled exploding of the fuel in the engine that
resulted in damage to the engine. He had discovered that the fuels of the day were incapable of withstanding the high temperature and pressures inside the engines’ combustion chambers. Via his testing, Midgley had discovered that the addition of small amounts of tetra-ethyl lead to gasoline, allowed the fuel to remain stable in the combustion chamber until ignited at the proper time. This was the first of the discoveries of the benefits of TEL in gasoline.

Also occurring in 1921, was the formation of the co-operative fuels research committee, known as CFR. The CFR was an early predecessor to what we now recognize as the ASTM. This group was comprised of well-educated petroleum engineers from countries in Europe and the United States. Even though these advances were occurring and engineers were beginning to study gasoline, it would still takes some more time to develop before this knowledge and technology was applied aviation.

For the most part, by 1922 aviation was still operating on unleaded fuels. Later in that year, however, the United States Army designed a test program to evaluate the use of TEL in gasoline for aviation applications. The Army tested the new leaded aviation gasoline in a Liberty engine with little success. The Liberty engine was a 1,649 cubic inch (27 liter) water-cooled 45° V-12 aircraft engine of 400 horsepower, designed by the Packard Motor Car Company for use in World War I. The engine and its variants were very successful in both aviation and surface based applications. The study of the Liberty engine concluded that there were severe problems, “due to excess additive being used,” and lead deposits (ASTM D910 Task Force of D02.J.02, 2004). As a result of this study, TEL was not implemented for use in aviation gasoline. It was not for another four years that TEL was revisited for use in aviation gasolines. This time, the United States Navy took a different approach than did the Army previously; the Navy researchers added tetra-ethyl lead directly into the aircraft tanks (Clark, 2007). This change allowed for a better control of the mixing of the TEL with the fuel and a more consistent blend of fuel to the aircraft engine. This better blending prevented the excessive lead problems found in
the Army tests. The very next year, due to the Navy’s success, the Army revisited the use of TEL on a limited basis. It was discovered through the ASTM Subcommittees research that the Army used a maximum of 3 mL/ Gal (ASTM D910 Task Force of D02.J.02, 2004). Even though both the Army and Navy were using TEL on a limited basis for their aircraft operations, the overall motor octane of the fuel that they were using did not exceed 100 MON, as it does today, rather was, “87 ON estimated, dependant on base-stock” (ASTM D910 Task Force of D02.J.02, 2004).

Due to the success that the United States armed services were noticing by using limited amounts of TEL in their aviation fuels, in 1928, “systematic evaluation of tetra-ethyl lead [to evaluate] anti-knock on performance of aviation engines [took place] at McCook Field” (ASTM D910 Task Force of D02.J.02, 2004). (McCook Field is now encompassed in the grounds known as Wright Patterson Air Force Base and is located just outside of Dayton, Ohio.) Following favorable test results, in 1930 the United States army specified that their aviation-grade gasoline should contain no more than, “3mL/gal” (Clark, 2007). Two years later a subcommittee of the CFR developed a method and a special research engine for testing motor octane number.

This method has remained widely unchanged even to this day. The following excerpt describes the process of obtaining a motor octane number, “octane ratings are determined in a special single-cylinder engine with a variable compression ratio (CR 4:1 to 18:1 ) known as a Cooperative Fuels Research ( CFR ) engine. [...] The head and cylinder are one piece, and can be moved up and down to obtain the desired compression ratio. The engines have a special four-bowl carburetor that can adjust individual bowl air-fuel ratios. This facilitates rapid switching between reference fuels and samples. A magneto-restrictive detonation sensor in the combustion chamber measures the rapid changes in combustion chamber pressure caused by knock, and the amplified signal is measured on a "knock-meter" with a 0-100 scale” (Faqs.org, 1996).
It is however important to understand that the United States was not alone in its quest for an anti-knock additive for aviation gasoline. Documentation was found that in 1934 the British had a specification for TEL in their aviation gasoline’s. The British specification was for a, “maximum of 4mL TEL/Imperial gallon” (Clark, 2007). At that time, the British were reporting that their fuels still only had an, “87MON,” which was derived on a, “special BAM engine” (ASTM D910 Task Force of D02.J.02, 2004).

During the mid thirties was discovered how to manufacture, iso-octane (2,2,4-Trimethylpentane) inexpensively. The discovery of this process allowed for an additive to boost the MON above 100, and subsequently the concept of +100 MON was born. As chronicled in the following excerpt, it was “…discovered that [engine] knocking stopped when 2,2,4-trimethylpentane was added. This was [also] the origin of the octane rating scale” (Totten, Westbrook, & Shah, 2003).

The concept of an octane rating scale was in essence a measure of how close fuels blended with TEL could perform when compared to a fuel that was pure iso-octane. On one end of the scale at 100 was a fuel made of pure iso-octane. Engine performance and engine knock was measured on this and the resulting performance of the fuel was deemed to be 100. On the far low end of the scale was pure unleaded gasoline. Engines were measured for performance on pure unleaded fuel, and this rating was deemed to be zero. As iso-octane was added to fuel, engine performance was measured. Engine performance was measured with various ratios mixtures of iso-octane and unleaded gasoline. Blends were made of every percent mixture: 99% iso-octane and 1% unleaded gasoline, 98% iso-octane and 2% unleaded gasoline, 97% iso-octane and 3% unleaded gasoline, etc. Engine performance was measured at every blend ratio. While Iso-octane was an excellent chemical for piston engine combustion, and for charting engine performance, it was not a chemical that was suitable for flight. So in place of iso-octane, TEL was added to fuel in varying amounts and tested. A small amount of TEL would make the engine perform, for example, as if the engines were running on a 50% blend of iso-octane and 50% unleaded gasoline. This fuel blend would be labeled 50 octane. When more TEL was added to the
gasoline and the engine performed as if it was running on 87% iso-octane and 13% unleaded gasoline, this blend was labeled as 87 octane. Varying amounts of TEL were added and painstakingly tested and compared to the iso-octane/unleaded fuel mix for every combination of blends. Finally when a sufficient amount of iso-octane was added to gasoline to make the gasoline behave as if it were really pure iso-octane instead of gasoline, this fuel was labeled as 100 octane. This rating system worked for all ratings up to 100 MON. This testing and comparison system was a long and tedious process, and the engine performance outcomes were highly dependent on the engine testing conditions and the test set up. And in the early years, there was variation in the test outcomes. The result was that more than one set of blending/performance charts emerged. For example the octane rating vs. engine performance charts for automotive engines took several forms and automotive engines differed from aviation engines. Over time a very precise test specifications were developed and generally agreed upon by the industry experts. Interestingly enough the aviation industry eventually settled on a blending/performance/rating system developed for automobile engines, hence the name Motor Octane Number or MON, as opposed Aviation Octane Number, or AON.

It is not well known why the aviation engine manufacturers elected to use automotive derived MON ratings instead of the AON ratings, however it is most likely due to the fact that the petroleum companies were making much more automotive fuel than aviation fuel and so the automotive expertise was much more widely understood and used. Today a few of the most knowledgeable aviation engine performance experts know that the MON ratings do not exactly match aviation engine performance, however, for nearly all engine performance measures, MON reflects aviation engine performance well enough. It is only in rare cases where highly scientific work is done on new fuels and engine performance that adjustments must occasionally reflect the fact that MON does not exactly predict aviation engine performance.
By the end of the 1930’s, there existed 14 grades of aviation gasoline in the United States. Unleaded fuel grades such as: 65, 73, 74, and 92 could be found. Due to the vast number of aviation fuel grades, records during this period provide varied information (ASTM D910 Task Force of D02.J.02, 2004). The ASTM Subcommittee studying the history of aviation gasoline, however, was able to discern some general guidelines that were used for blending aviation gasoline. Essentially, low-octane aviation fuel grades were “often unleaded, but TEL [was] permitted avgas grades greater than or equal to 80 MON. There existed a limited amount of ’92 Army’ (which was leaded), [all others typically] 87 MON unleaded avgas” (ASTM D910 Task Force of D02.J.02, 2004). By the beginning of the 1940’s, aviation fuel was still isolated and separated from the automobile fuel supply chain; however, the preference for aviation gasoline remained largely unleaded.

The 1940’s also brought about the Second World War. In the Allies attempt to win the air war waging over Europe with Adolf Hitler’s Luftwaffe, aviation was rapidly advanced. WWII saw the advent of the largest and most demanding aviation engines ever developed. Engines such as the Rolls-Royce Merlin V-12 were powering such aircraft is the British Supermarine Spitfire, in an attempt to regain the balance of power in the skies over Western Europe in the early parts of WWII. Fuels technology was also rapidly improving to keep pace with the aircraft engine improvements. In 1942, the Supercharge Rating Test was introduced. The supercharge rating was developed as these new, powerful engines were fitted with supercharging systems, which allowed a mechanical or turbine operated air compressor to substantially increase the pressure of the air being fed to the engines. By boosting the intake air pressure, engines could maintain high levels of horsepower at high altitude where the air was less dense. Low density air at high altitude reduced the power available from the engines, but supercharging allowed engines to maintain their power at high altitude. At low altitudes, supercharging could force more air into the engine and give it even more power that it would normally have. The effect on supercharging, however, was that the engine performance vs TEL levels did not match the earlier testing
done on non-supercharged engines (called normally aspirated) when the original octane rating system was created. The result was testing to map engine performance vs TEL in supercharged engines. This mapping then resulted in the supercharge rating for aviation gasoline. Also in 1942, leaded military fuels in excess of 100 MON & 125 PN (supercharge number) were being used, the name of this fuel was quickly changed to be called 100/130 (ASTM D910 Task Force of D02.J.02, 2004).

Grade 100/130 is what pilots today recognize as ‘green avgas’, because of the green dye put in the gasoline to make it recognizable as a high octane fuel. Green 100/130 gasoline persisted on after WWII, and into the heyday of general aviation aircraft production of the 1950’s through the 1970’s. Despite the fact that the green 100/130 fuel was discontinued in the mid 1970’s in an effort to reduce airborne lead emissions, most general aviation aircraft are actually still certified on 100/130 Avgas. The ASTM Subcommittee document also found that in 1942 the industry at large, “starts to rationalize the grades” (ASTM D910 Task Force of D02.J.02, 2004), to cut down in the number of different grades that were available. This reduction was, most probably done in an attempt to and streamline fuel production /delivery logistics for the war effort. Between 1942 and the end of WWII in 1945, near the end of the WWII, grade 115/145 Avgas was introduced. Many older aviators today referred to 115/145 as “the purple avgas” or “grape juice,” as it was unofficially called. The “purple” was in reference, the purple dye, again used to distinguish the 115/145 fuel from its lower octane counterparts. By the end of WWII massive 4360 cubic inch engines were being produced with extreme amounts of supercharging. These 28-cylinder behemoths produced well over 2000 horsepower and allowed for large aircraft to fly at previously unattainable high altitudes for very long distance. The engine demands on the fuel to produce this kind of horsepower were tremendous, and so the 115/145 fuel was developed with 8 mg of TEL per gallon. Oldtimers who maintained these engines could testify that just as the U.S. Army had found in the early days of TEL testing, these extreme amounts of TEL would routinely cause problems for the engines, such as spark plug fowling, sludge in engine oil, carbon buildups in intake and exhaust
manifolds, and lead contamination of turbocharging systems. These high performance engines required a high degree of maintenance to compensate for the issues created by the large amounts of TEL. However, it was only the use of the TEL that enabled these giant piston engines to perform at the levels required to propel the aircraft of the day. It was in no small part to the performance of these engines that allowed the Allied aircraft of WWII to rapidly bring to close a war, that in the early years, the British forecast would last for decades. Both 100/130 and 115/145 was what would power the Allies to victory in WWII over Nazi Germany’s Luftwaffe in May of 1945, and the Imperial Japanese Air Force in June of that same year.

Following WWII, it was recognized that something needed to be done to standardize and legitimize aviation gasoline with the ASTM. In 1946, ASTM D02 Subcommittee J on Aviation Fuels was officially formed (George E. Totten, 2004). The result of this Subcommittee’s work took shape in the form of a tentative specification for aviation gasoline presented in 1947. The specification known as ASTM D910 -47T was voted on, and approved by the end of that year. D910 specified, “Two grades of aviation gasoline, known as: Grade 91-98 & Grade 100 -130 ” (American Society for Testing and Materials, 1947). The new specification separated the “grades of aviation gasoline differing in lead content, color, and octane numbers” (George E. Totten, 2004). It was apparent that this first ASTM specification for aviation gasoline, encapsulated all of the existing gasoline knowledge that had been gleaned over the first 44 years of powered human flight. Upon the publication of the D910 specification in 1947, the National Bureau of Mines conducted a market survey and collected data on aviation gasoline, the survey, “indicated the majority of Grade 80 Avgas production as unleaded, with all higher octane Grades containing lead” (Holliman, Barker, & Potts, 1948). In the same year this report was released, Grade 115/145 first appeared on ASTM D910.
In 1951, an examination of the history of Avgas revealed that in addition to D910 a second specification appeared; a military specification (known as a MIL-SPEC) for aviation gasoline - MIL 5572 (Clark, 2007). During this same time, other grades began to surface, such as: 80/87, 91/96, 91/98, & 108/135 (ASTM D910 Task Force of D02.J.02, 2004). Few of these grades actually made it onto D910. Grade 80/87 appeared on D910 as ‘Grade 80’ and grades 91/96 and 91/98 appeared as ‘Grade 91;’ these were both leaded fuels and continued to exist on the most current revision of D910 as of 2007 (ASTM International, 2007). In 1955, another study completed by the National Bureau of Mines indicated, “a move to almost exclusively leaded AVGAS across all Grades with only one, Grade 80, sample out of seventeen being unleaded” (Blade, National Annual Survey of Aviation Gasoline and Aviation Jet Fuel, 1955). A 1960 (Blade, Avition Fuels, 1960, 1961) report published by the same agency, showed similar findings.

In the 1960’s, with the changeover of high performance aircraft to jet power and jet fuel, and with over six potential grades of avgas and the demand for aviation gasoline on the decline, the industry felt that it must once again complete a “rationalization of Grades in market to largely 80/87 and 100/130” (ASTM D910 Task Force of D02.J.02, 2004). Despite this drive to reduce the number of grades of gasoline, however, the only grade that was removed from D910 was the grade 115/145. In the 1962 version of D910, the following grades were listed, “80/87 (Grade 80), 91/98 (Grade 91), and 100/130 (Grade 100)” (American Society of Testing and Materials, 1962). With regard to max lead content and how each fuel was defined, 1962 specification listed, “the following information: Max TEL (ml/gal), Grade 80-87 = 0.5 (dyed red), Grade 91-98 = 2.0 (dyed blue), & Grade 100-130 = 3.0 (dyed green)” (American Society of Testing and Materials, 1962).

In relation to minimum lead content, “Grade 80-87 = 0, per note d” (ASTM D910 Task Force of D02.J.02, 2004). The specification goes on to clarify in Note d, “If mutually agreed upon between the
purchaser and the supplier, Grade 80-87 may be required to be free from tetraethyl lead. In such a case, the fuel shall not contain any dye and the color as determined in accordance with Method D156” (American Society of Testing and Materials, 1962). This was one of the rare instances where fuel listed in D910 actually had a minimum of zero of TEL to be included in the fuel blend. This zero lead reference in the D910 spec was later removed; meaning that all fuels contained in this specification, then had to contain TEL with the maximum being called out for each grade of fuel. This meant that any unleaded fuel designed to be used as aviation gasoline could not comply with ASTM D910 as written in 2011.

This quirk in logic would later cause interesting logic problems for both the ASTM and the FAA, in the 1990’s and the 2000’s as attempts progressed to certificate and deploy unleaded fuels to replace leaded fuels exactly. The problem would become that any fuel specified as an aviation gasoline according to D910 spec, had to contain TEL. Any unleaded fuel, even if the fuel exactly replicated the leaded fuel, could not be used in an aircraft because an unleaded fuel could not be included in the D910 specification as an aviation gasoline. Only aviation gasoline was legal to be used in U.S. type certificated aircraft. This circular logic created two decades of logistics problems and debate within the industry experts of the ASTM and the FAA at the end of the 20th and beginning of the 21st centuries.

In the 1970’s, the last major changes occurred to the aviation gasoline specification. There was a movement to once again to reduce the number of aviation gasoline grades. ASTM proposed, “to rationalize Grade 80 and 100/130 to one fuel (dyed red), Grade 100LL (100 low-lead) (dyed blue),” this new fuel would, “retain the octane rating of 100/130 but reduce maximum TEL content to 0.56 g Pb/L” (ASTM D910 Task Force of D02.J.02, 2004). In 1971, aviation gasoline Grade 100LL was born. This was reflected in 1972 as the United States began the gradual move to one grade of avgas, 100LL. Initially, this did not mean that all of the other fuel grades were abandoned, they were still available to the
consumer; however, there existed a “minor supply of other products e.g. Grade 80/87, 100/130, 91/96 etc” (ASTM D910 Task Force of D02.J.02, 2004).

The move to the 100LL fuel was due in no small part to pressure from the United States Environmental Protection Agency (EPA). In 1970, the EPA issued the Clean Air Act of 1970. Contained within that act was the requirement for the use of catalytic converters on automobiles to meet emissions requirements in the United States. When leaded fuels were combusted in automobile engines, the tetra-ethyl lead plugged the tiny honeycomb passages of the catalyst matrix, and coated over the catalyst material contained in the catalytic converters. The lead would then render the catalyst ineffective and would plug the exhaust flow from the engine, thereby eventually preventing the engine from running. By the late 70’s & early 80’s, the United States saw a complete phase-out of leaded automobile gasoline. The 1995 version of the Clean Air Act “banned leaded motor fuels altogether for road use” (Passavant G., 2009). This left general aviation gasoline as being one of the only fuels left in the United States to contain tetra-ethyl lead. The EPA largely left general aviation gasoline on regulated by subsequent versions of the Clean Air Act due to lack of alternatives to 100LL. The EPA was also lenient on the use of lead in aviation fuels in the later decades of the 20th century, due to influence from the United States Air Force. In the 1970’s and 1980’s the U. S. Air Force was still a principle user of leaded aviation gasoline for national defense purposes. Despite the widespread use of jet aircraft the Air Force still had a strategic need for piston powered aircraft. While not published anywhere as an official position by the FAA, the ASTM, or the Department of Defense, those associated with the D910 committee over this period generally acknowledge this understanding between the EPA and the leaded aviation fuel producers/users. By 2000 the Air Force had abandoned all support for aviation gasoline, based on the fact that the Air Force had retired all of its piston powered aircraft. So by the early 2000’s, with unleaded fuel no longer a national defense need, the EPA once again began looking at leaded aviation fuel as a target for elimination.
It is ironic to note, however, with regard to U.S. Military gasoline use, that the deployment of large numbers of Unmanned Aerial Vehicles (UAV) in the wars following the September 11 attacks on the U.S., has created some small amount of renewed interest in aviation gasoline by the DOD. Many small UAV’s take advantage of the gasoline powered piston engine coupled to a propeller as a very efficient propulsive means for these small aircraft. While unleaded automobile fuel has generally proven satisfactory for UAV’s, it is also recognized that a high octane fuel would greatly enhance the range and payload capabilities of these small aircraft, just as it did for the piston powered aircraft of WWII. There is little reason to suggest that the DOD plans to attempt to resurrect high octane leaded fuels for UAV’s. There is however also little doubt that if a high octane, high heat content unleaded fuel emerges, that the DOD would be very interested.

For those not acquainted with the rational for the EPA’s position on lead, a brief toxicological discussion is warranted. Since the days of the Romans, lead has been an aid to civilized living. This easily malleable metal proved useful things like, indoor plumbing for both fresh water and waste water. Before the ability to easily manufacture steel or copper pipes, lead pipes could be easily made and connected by flame soldering. Lead added flexibility to paint and allowed paint to expand and contract as wood and steel changed temperature. Lead became very popular in paint for over a century. Unfortunately, continued exposure to lead has some harmful side effects in humans, and presumably other creatures. When ingested, typically by mouth, lead is taken into the bloodstream where the body’s liver attempts to filter it out. Because lead is so stable, once filtered by the liver, the liver cannot purge the body of the lead. The result is liver failure. Additionally, lead can tend to settle in the brain causing motor skill and cognitive brain disorders. These problems are especially harmful to small children. Because small children tend to put EVERYTHING in their mouths, they tend to be more exposed to lead from any source. Studies also tend to show that once ingested the lead seems to do more harm, especially to the brain of children. Given the choice between flying airplanes and protecting
small children, the position of the EPA is easy to understand. Debate continues to this day regarding acceptable levels of exposure, testing methods, and how public policy is to be enacted, however, the EPA holds the high ground in this battle so there is no doubt that end of use of lead in motor fuel is in sight in the foreseeable future.

Over the years since 1972, aviation gasoline specifications remained largely unchanged. However, just because the specification exists there needed also to exist a viable market for producers and distributors to supply. As quality control concerns arose, and aviation accident litigation cases grew exponentially in the late 20th century, producers and distributors rapidly moved towards the single fuel option at the beginning of the 21st century, 100LL. Grades 80 and 100/130 quickly became extinct across North America to general aviation pilots and aircraft owners. Aircraft that were designed to run on the 80 octane gasoline were upgraded to run on 100LL, and most all of the airplanes that were certified to run on 100/130 were also dual-certified to run on grade 100LL. In most of these cases, dual-certifying these aircraft consisted of merely filing additional paperwork. Even new production aircraft today, such as the Cirrus aircraft, were dual-certified to run on fuel Grades 100LL and 100/130, even though Grade 100/130 was not available in the continental United States where the flight testing of the aircraft was conducted.

This move to a single fuel, 100LL, was not a completely painless transition for general aviation. Aircraft designed to run on Grade 80 tended to experience more lead fouling of spark plugs, oil sludge, and lead continuation of engine systems. The 100LL at 2mg of lead per gallon contained more than four times the lead of the grade 80 that it was replacing (0.50 mg per gallon). The engines designed to run on the 100/130 (green) fuel did suffer some performance losses with the lower octane fuel. Many of the performance losses were not felt by the typical user, since in most engines there was some margin designed into the engines, to account for worst case low octane ratings in random batches of fuel.
There was, however, range and power loss for many of the very high performance engines. In the early
days of the changeover to 100LL, there were problems with engine valve failures, and valve cracking
since lead, both lubricated the valve guides, and provided a good metal to metal contact of the valve
faces for valve cooling. Despite inconvenience and additional expense to the aircraft operators, these
valve train problems were resolved via the use of improved materials. By 2011, stories of lead being
needed for long engine valve life, or being a player in valve failure, remained only as airport legends, and
were not considered to be problems in modern engines.

The history of aviation gasoline and the ASTM D910 specification reflect over 105 years of
practical experience & through trial and error. The information contained in today’s version of the
specification is comprised of the building blocks of years past. Aviation gasoline has become the most
regulated and specification controlled non-nuclear fuel on the face of the planet. This is quite
impressive considering that today’s most advanced piston aircraft still continue to operate on a fuel that
has remained essentially unchanged since 1972. The future is pointing toward unleaded aviation fuels,
with the industry, the government, and users demanding it more and more each day. It is clear
however, that ASTM D910 is intended only for leaded aviation gasoline; therefore, alternative
specifications with the same rigor and attention to detail as D910 must be sought. After decades of
debate, the logic problems created by introducing and unleaded fuel into D910 are insurmountable.
There is hope for unleaded aviation gasoline, however, ASTM has committed to the development of a
new aviation gasoline specification just for unleaded fuels. They have also committed to the
development of specifications for aviation fuels created from non-petroleum sources. This work
continues to build on the lessons learned from nearly a century of aviation fuel development and engine
experience. These new fuel specifications are building on both the good and bad lessons learned. As we
move forward into the next millennium of flight, and the fuels that are to power future general aviation,
we must be ever mindful of from where aviation gasoline has come, and the lessons learned along the way.
**Historical Timeline of Unleaded & Leaded AVGAS Development**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1903</td>
<td>Wright brothers - first gasoline aviation engine. No aviation fuel specifications, automotive gasoline utilized.</td>
</tr>
<tr>
<td>1917</td>
<td>85th &quot;Neoplane Gasoline&quot; Unleaded light hydrocarbon product specific to aviation introduced to increase flight safety/reliability.</td>
</tr>
<tr>
<td>1918</td>
<td>Domestic, Export (Grade X), and Fighting Grades - Unleaded straight run gasoline</td>
</tr>
<tr>
<td>1921</td>
<td>TEL discovered by General Motors</td>
</tr>
<tr>
<td>1921</td>
<td>Co-operative Fuels Research Committee (CFC) formed.</td>
</tr>
<tr>
<td>1922</td>
<td>US Army tests TEL led aviation gasoline in Liberty engine. Severe problems due to excess additive being used &amp; lead deposits. TEL not adopted in aviation fuel.</td>
</tr>
<tr>
<td>1926</td>
<td>US Navy starts using TEL by adding directly to aircraft tanks.</td>
</tr>
<tr>
<td>1927</td>
<td>US Army starts using TEL on a limited basis. 3 ml/gallon maximum.</td>
</tr>
<tr>
<td>1927</td>
<td>Edgar proposes 'The Octane Scale'</td>
</tr>
<tr>
<td>1928</td>
<td>Start of systematic evaluation of TEL/anti-knock on performance of aviation engines at McCook Field (Wright Field)</td>
</tr>
<tr>
<td>1930</td>
<td>US Army Specification 3 ml TEL/gallon maximum</td>
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<tr>
<td>1932</td>
<td>Octane Scale/CFR Engine Developed</td>
</tr>
<tr>
<td>1934</td>
<td>British Specification 4 ml TEL/imperial gallon maximum</td>
</tr>
<tr>
<td>1936</td>
<td>Inexpensive process for iso-octane manufacture (100 MON) discovered.</td>
</tr>
<tr>
<td>1937</td>
<td>14 Grades of US aviation gasoline: 65, 73, 74&lt;sup&gt;th&lt;/sup&gt; Grades unleaded. Limited amount of 92&lt;sup&gt;nd&lt;/sup&gt; grade unleaded. (*) = Army octane method where 92 ON about 87 MON, TEL permitted in Grades &gt; = 80 MON.</td>
</tr>
<tr>
<td>1942</td>
<td>Supercalque test introduced. Military fuels 100 MON, 125 PN Supercalque, then changed to 90/130.</td>
</tr>
<tr>
<td>1947</td>
<td>Tentative ASTM D910 AVGAS Specification</td>
</tr>
<tr>
<td>1947</td>
<td>Majority of Grade 89 unleaded. Higher octane grades all leaded - National Bureau of Mines Survey</td>
</tr>
<tr>
<td>1951</td>
<td>MIL 5572 and ASTM D910</td>
</tr>
<tr>
<td>1954</td>
<td>Majority of Grade 89 leaded. High octane grades all leaded - National Bureau of Mines Survey</td>
</tr>
<tr>
<td>1960’s</td>
<td>Rationalization of Grades in market to largely 88/87 and 100/130</td>
</tr>
<tr>
<td>1971</td>
<td>Proposal to rationalize Grade 89 and 100/130 to one fuel, Grade 100LL. Retain octane of 100/130 but reduce maximum TEL content to 0.56 g PhA.</td>
</tr>
<tr>
<td>1972</td>
<td>Gradual move to one AVGAS Grade, 100LL, with minor supply of other product: e.g. Grade 80/87, 100/130, 91/96 etc.</td>
</tr>
</tbody>
</table>

All fuels unleaded

Unleaded except on limited basis

Information mixed. Low octane grades often unleaded but TEL permitted in > = 80 MON AVGAS Grades. Limited amount of 92 Army 87 MON AVGAS unleaded.
Chapter # 2

ASTM D910 - The Backbone of Aviation Gasoline

As one has by now gathered, aviation gasoline today has been a work in progress since the first specification was introduced in the mid 1940’s. The ASTM D910 is the result of years of experience by all involved with the handling and use of aviation gasoline. Before alternatives to 100LL are examined, one must first understand the D910 and all of its subtleties. D910 has been tweaked throughout the years as more has been learned during the operation of the fuels it specifies. Most tend to think that when a new fuel is produced, the FAA should have the final say so on the fuel’s certification. This is not entirely true, nor should it be. The FAA Administrator, Randy Babbit, recently discussed the FAA’s position on this topic; he said that, “the FAA does not certify whether or not a fuel is viable, it (the FAA) leaves that call to the ASTM and other industry groups” (Babbit, 2010). Mr. Babbit went on to say that, “the FAA will continue to support this industry-wide process of certifying an unleaded fuel” (Babbit, 2010). However, those that aim to circumvent the ASTM process are doing so because of commercial interests rather than ultimate safety of flight. In 2010, an alternative fuel developer seemed to think that Mr. Babbit should have taken another approach. Another alternative fuel producer said that he felt, “the ASTM process is archaic and unnecessary,” and that “we (the company he represents) should not be held up by the grey-beards at ASTM” (AvWeb, 7). At first inspection it may seem that this is a statement, which is logical and well founded; however, once one realizes that ASTM and its members representing aviation interests from around the world view safety of paramount importance, this argument begins to dissolve. While it is not that his public comments reflect an intention to produce an unsafe product, quite the contrary, this gentleman is also an expert in his field and is just as committed anyone else in aviation to safety. This author only mentions this as a specific example of a difference of opinion between preeminent experts in aviation fuels. Where more than one expert exists, there is guaranteed
to be more than one perspective on a solution. The function of ASTM and the spec process is to bring these alternatives before experts from around the globe, and discuss the merits of these ideas in a highly structured and open forum. The process can be slow, since most of the ASTM participants are volunteers and have other full time professional jobs. The slowness of the process is also its, elegance and power. The presentation, review, discussion, balloting, revision and resubmission process, allows experts from every facet of aviation to examine the proposal and to improve it. Peer criticism can be frustrating and time consuming. However, there have been many more failed fuels than approved fuels over the past 100 years. Some failures came as fuels were used, in these cases there is the potential for loss of life. As such the ASTM committee members take their responsibility to fully examine a new fuel very seriously. The power in ASTM is that it brings experts from areas where an individual expert might not otherwise have knowledge. Many bad fuels have been revealed over the years due to the length of the ASTM process.

It is understandable that the developer of a good fuel will be frustrated that the world does not embrace the fuel immediately. When the developer KNOWS it is a good fuel, and it actually IS a good fuel, the slow pace of spec certification can be frustrating beyond belief. However, it is not good enough for just the developer to know the fuel is good, all of the parties affected worldwide, including the producers, the transporters, the engine manufacturers, the airframe manufacturers, the aircraft component manufacturers, the EPA, the FAA, and the users, need to know how a new fuel affects them. So while slow, it is better to take time for EVERYONE to know what the fuel does, rather than risk the consequences. As they say, when the engine quits on the airplane, you cannot just pull off to the edge of the road. And in any professional organization there are differences of opinion on technical concepts, that is the unfortunate side effect of public scrutiny, but over time public peer review has proven to be the best way to resolve technical issues.
Given all of this, the ASTM D910 specification, and the D910 spec committee, would seem like a logical place to start if one were attempting to develop a unleaded replacement for 100LL. As the title indicates D910 is the, “Standard Specification for Aviation Gasolines.” In the scope, it states that, “This specification defines specific types of aviation gasoline for civil use. It does not include all gasoline satisfactory for reciprocating aviation engines. Certain equipment, or conditions of use, may permit a wider, or require a narrower, range of characteristics than is shown by this specification” (ASTM International, 2007). It would seem then that based on this scope, this would be the appropriate specification for and unleaded replacement to 100LL; that is of course however, until one gets down to section six. In section six, materials and manufacture are discussed. This is where the following statement on mandatory additives is found, “Tetraethyl Lead, shall be added in the form of an antiknock mixture containing not less than 61 mass % of tetraethyl lead and sufficient ethylene dibromide to provide two bromine atoms per atom of lead” (ASTM International, 2007). This is where any unleaded fuel, meant to replace 100LL, would become disqualified for inclusion in D910. This statement alone requires the mandatory inclusion of tetra-ethyl lead into any fuel that occupies this specification. The ASTM has proven time and time again that they are unwilling to remove this requirement. It is generally felt by ASTM members that only leaded fuels be covered by D910 and that any unleaded fuels be covered by another specification. Therein lies the problem, since D910 and 100LL have been the single source fuel and single source specification covering aviation gasoline since 1947; airframe manufacturers and engine manufacturers have referred to ASTM D910 as the only certification a fuel must achieve to be certified for use on their airframe and engine type certificates.

So why doesn’t ASTM simply remove the reference to lead in the D910 document? At first this would seem to be the quickest solution to the problem. The obstacle to this, are the individual ASTM members on the D910 committee who represent the various airframe, powerplant, component, manufacturers, representatives of the gasoline distribution system, and the FAA. The best way to
illustrate the problem is by example. In this example, Cessna is used for illustrative purposes. Cessna is not used here for any reason other than they are a universally known aviation company with hundreds of thousands of aircraft worldwide, that they are the foremost leader in general aviation for research on fuel related research. So say for example that Cessna has certified their aircraft, based its performance, and the durability of all of the fuel system components based on a D910 spec fuel. As a result, the Type Certificate Data Sheet supplied to the FAA. The Type Certificate Data Sheet, or TCDS as it is commonly known, provides key performance data of the aircraft based on the fuel on which the aircraft is operated during the flight certification process. Parameters such as airspeed, power settings, rate of climb, fuel consumption, take off distances, related aircraft instrument markings, operating instructions, and methods are all established based on how the aircraft operates on the fuel used during certification.

In addition to flight parameters, the materials used in the aircraft’s fuel system are based on the chemical composition and characteristics of the fuel used for the aircraft design. Since Cessna purchase components from suppliers and vendors, everyone who makes a part and sells it to Cessna for use on the aircraft is basing the design of these parts on the type of fuel used. Once parts are determined fit for use on the aircraft being certified, the design of these parts are frozen, and the FAA controls the design of these parts through separate certification processes, known as either a Parts Manufacturer Authorization (PMA), or a Technical Standard Order (TSO). Once accepted on the list of approved parts for the aircraft being certified, changes cannot be made to these parts without recertification of either the individual parts or the aircraft as a whole. This process is known as configuration control. Configuration control is the only way that the performance parameters of the aircraft and its related systems can be maintained. If random changes are allowed to even seemingly insignificant parts on the aircraft, it is possible that any one change, or an accumulated effect of many small changes, could alter the way the aircraft operates. Random changes in how aircraft operate are not acceptable, since flight crews must depend on the fact that all aircraft of a particular make and model, all perform as near
identically as possible. Even changes to the aircraft that improve its performance in a positive direction, can result in operation of the aircraft that can result in structural damage to the aircraft, under extreme conditions.

What does the concept of configuration control have on the decision by ASTM not to simply remove the requirement for lead from the D910 specification for fuel? Quite simply, the aircraft was not certified on unleaded fuel. From a philosophical point of view, if the fuel is changed, the aircraft cannot be operated in the same manner as it was originally certified. Maybe the aircraft can perform the same way and maybe it cannot, but if the fuel is changed, the aircraft model, and all related components, would have to be re-certified on the new fuel. There are processes for doing this, but they are cost prohibitive. Unless someone with enough money can do the recertification, a change to the D910 specification could result in every aircraft becoming non-compliant with that aircraft’s Type Certificate Data Sheet. While Cessna is among the largest of the general aviation aircraft manufactures, even Cessna does not have the funding for these types of re-certifications.

What is described in the previous paragraph addresses only the logic problem, where there may even be no detrimental effect on the aircraft or its components. The importance of configuration control is further complicated if a change in the fuel specification actually did have a negative effect on some components in the aircraft’s fuel system. First re-certification testing has to be done to verify whether there IS any negative effects, and if any are found now expensive changes to design must be made to correct the negative effect. These corrections then result in further complications to the parts supply system and to the technical standards to which the aircraft are maintained.

While it would seem that for the elimination of lead from fuel, the expense would be justified, the problems is that fuel is not the only part of the aircraft that is competing with funding for design changes in the general aviation fleet. There are hundreds of changes in the system at any given point in
time, for things ranging from serious safety of flight issues, to changes necessary because vendors have gone out of business and new sources of parts must be certified to keep the existing fleet operational in its original configuration. Keeping fleets of aircraft in the air is an expensive endeavor and the amount of money available is very limited. As a result, the aircraft manufacturers, the FAA, and the ASTM are extremely hesitant to make changes that have fleet wide effects on the certification of aircraft.

All hope for an unleaded replacement fuel is not lost though; the industry and ASTM alike have attempted to devise a solution predicated on the history and knowledge contained within D910, without placing restraints for future unleaded fuels. ASTM has had in place since early 2008 a task force formed to develop a separate “Specification for Unleaded Aviation Gasolines.” The new specification is known as ASTM D7547. D7547 is essentially a duplicate image of D910, but removes the requirement for a mandatory additive of tetra-ethyl lead. This makes the evaluation of this new specification for those in the industry, and the FAA who must now implement it. Why? Because not the established fuel, on which most of the piston engine fleet is certified, remains untouched. Even when D7547 is eventually approved, it does not replace D910, but instead adds another fuel option. Once there becomes two fuel options, D910 and D7547 are approved, then new aircraft can be certified on either one or both fuels. Existing aircraft can be re-certified on as needed basis, where the re-certification process can be prioritized based on the individual needs of a particular model of aircraft, the amount of fuel consumed, and the economic viability of performing a re-certification on a particular model of aircraft.

This is a topic that is explored in greater detail in later chapters. With all of this in mind it becomes clear why a person must first understand why each section of D910 exists, and the specification is composed the way it was in D910.
Section one, already discussed, is the scope of the specification. The scope is intended to tell producers and users what the specification is designed to cover. In D910, the scope says that the specification, “covers formulating specifications for purchases of aviation gasoline under contract and is intended primarily for use by purchasing agencies […] and that it] defines specific types of aviation gasolines for civil use” (ASTM International, 2007). Aviation gasoline in 2011 is distributed by six major distributors in the United States (C. Sincock, personal communication, 2008). Due to the highly litigious nature that surfaces after general aviation accident, these distributors must be extensively insured if they are to carry and distribute the product. Since the fuel is required to meet very precise specifications, “jobbers” (or fuel distributing contractors) are unable, under these insurance policies, to hold a fuel at the airport. Therefore, the task of distributing all of the nation’s avgas falls solely on the hands of these six distributors.

Refineries use D910 as not only a recipe guideline, but a quality control document to ensure that the six distributors are picking up from the fuel refiner, an “on-spec” product. After the refineries make a batch of 100LL the fuel is sent to an ASTM approved laboratory for D910 testing. The tests are done to verify the physical properties of the fuel, the fuel’s chemical composition, and to verify that the fuel meets the specifications stated in the D910 document. If the fuel passes, it is then given a certificate of (COA) analysis proving that the fuel is “in specification.” When the distributor picks up the certified fuel, the certificate of analysis follows that batch of fuel to the individual airports. It is upon delivery that the airport receiving the fuel is given the certificate of analysis to prove that the batch of fuel they are receiving was on-spec at the time the fuel was batched and tested. In section four of the D910, it addresses this topic of when the fuel is certified in the following way, “This specification, unless otherwise provided, prescribes the required properties of aviation gasoline at the time and place
of delivery” (ASTM International, 2007). Although this somewhat describes the process, the standard approach by producers and distributors test the fuel at the time of production, rather than at the place of delivery (fueling the aircraft). “Delivery” as stated by ASTM is generally accepted as delivery from the refiner to the fuel distribution system, as opposed to delivery to the airport, or delivery to the aircraft.

The point in time between production at the refinery and pumping into the airport fuel tanks can sometimes be a matter of months. Nonetheless the system used by distributors and manufacturers has allowed for safe transit and delivery of the United States’ avgas supply for nearly 60 years.

It should be noted that one other specification is used in the United States to ensure the quality of fuel begin delivered to the aircraft. Since the fuel receives its certificate of analysis when the fuel leaves the refinery and enters the national fuel distribution system, there is a potential for bad things to happen to the fuel while being transported, stored, and pumped into aircraft. This quality control is beyond the scope of ASTM.

The one minor hiccup to a potential new fuel being certified by the FAA, and not covered by an ASTM specification, is that the fuel distributor’s insurance policies only cover fuels that are covered by an ASTM certification. This point seems ardently stressed by the distributors at ASTM meetings. In 2008, a representative for AvFuel, the nation’s largest independent (non oil company branded) distributor, said, “We will not carry a product that is not covered by an ASTM certification” (C. Sincock, personal communication, 2008). This statement was made in reference to the insurance implications of distributing a non-ASTM certified fuel.

Also contained in the first couple sections of D910 is a list of referenced ASTM specifications used to compile D910. Section three contains a list of definitions as they pertain to the specification. In section five is the classification area. The classification area is where all of the grades of aviation gasoline covered by the current D910 specification are listed. It is unlikely that additional grades are to
be added to this section in the future, rather it is expected that current existing grades shall be deleted as time goes on.

Section six is the last section of the preamble of the D910 specification. The first part of section six defines from what that the aviation gasoline defined in the D910 specification should be made. It reads, “Aviation gasoline, except as otherwise specified in this specification, shall consist of blends of refined hydrocarbons derived from crude petroleum, natural gasoline, or blends, thereof, with synthetic hydrocarbons or aromatic hydrocarbons, or both” (ASTM International, 2007). Here again it can be seen why there is a problem with using D910 as the place for the definition for future unleaded fuels. In the future it is very likely that alternative sources for fuels lies beyond petroleum. Fuels including both jet fuel and gasoline derived from agricultural sources, algae, or even fuels that are created chemically through totally synthetic means are not only possible, but probable. It is becoming increasingly likely that the next generation of aviation gasoline shall come from a non-petroleum source. By using the statement listed in D910 saying that all fuels, “shall consist of blends of refined hydrocarbons derived from crude petroleum” (ASTM International, 2007), the specification immediately disqualifies any second generation and beyond fuels. Here again, this is where the new D7547 specification comes into play. This new specification does not restrict the source of gasoline to traditional petroleum crude oil sources.

One other area that is delved into in section six of the specification is what dyes shall be used to indicate grade of fuel under this specification. The following colors are mentioned: blue, yellow, & red. From these dyes all the colors of the different grades of aviation gasoline can be identified. The dye is not a part of the manufacturing process for the fuel, nor a result of the refining, but is rather simply and identifying color that is added to the fuel at the time of delivery into the distribution system. The only purpose of the dye is to enable the users to distinguish one grade of gasoline from another. Where an
aircraft must operate on one particular grade of fuel, the dye allows the user to know that the proper grade of fuel is being put in the aircraft. This is the last section that appears in the preamble of the specification. The next section to appear is the actual table of properties, which is the real backbone of the specification; technically it is in the middle of section six however, most people view this as the specification itself.

![Figure 1 - Table 1 from ASTM D910](image-url)
Figure 1 above shows the Table 1 of D910. It is the Rosetta stone of the different grades of aviation gasoline. Described within Table 1, at the top are the current 4 grades of aviation gasoline. This is where the grades are differentiated by MON, RON (supercharge number), and by color. In this part of Table 1, each of the grades are differentiated and are distinctly different. One also notices in this area that the maximum amount of TEL is specified for each grade. After the dye requirements are listed, the table morphs into one column of requirements. Listed are the “requirements for All Grades” which apply to all of the previously mentioned grades. These 23 tests, based on performance and not recipe, and their associated limits are the result of years of real-world experience. All of the tests listed are references to additional ASTM tests which instruct the proper methods of conducting each test. In regards to a new fuel coming to market, there are very few items in this table which can be altered in some sort of new specification. Basically put, this table is the fingerprint of aviation gasoline, any new fuel would have to closely resemble if not match this fingerprint to be successful as a replacement.

Looking at Table 1 in-depth reveals some very interesting things. Further explained throughout the remainder specification is the rationale of why each item was set as it was. This is the real interesting part of the D910. Most specifications do not go into this level of detail of chronology; however, since D910 is over 60 years old, the D02 committee covering D910 feels this is an important part of the specification itself. This table has ensured that the major items of importance to operation in an aircraft have remained unchanged. Since D910 is a performance based specification, and not a recipe for aviation gasoline, it is important to address things like additives. According to the D910, additives “may be added to each grade of aviation gasoline in the amount and of the composition specified in the following list of approved materials. The quantities and types shall be declared by the manufacturer. Additives added after the point of manufacture shall also be declared” (ASTM International, 2007). This refers to a list, which is contained in an ASTM research report. The list itself is beyond the scope of this examination; however, it is of importance to show that the D02 committee has
true thought of just about every are that could cause unsafe operation. When this list is compared to
the original daft of the specification from 1947, it can be found that additives are not even mentioned or
called out in any one section of the specification. (American Society for Testing and Materials, 1947).
This leads one to believe that over time, as different additives have been found not to work in leaded
avgas, D02 began to compile a list of known acceptable additives. ASTM, then crafted D910 to refer to
that list and thus compatibility with additives has become a requirement of the specification.

A person can find in the Appendix of the specification, this chronology of the D910 standard and
the rationale for each item included in the Table 1. The Appendix contains “Nonmandatory
Information,” meaning that the information contained in this specification is only for clarification, and
not a requirement of certification under this specification. To the casual reader, this section is often
overlooked. But by examining this section further, one begins to get a clearer understanding of why this
specification has become one that defines the, “most highly regulated fuel on the face of the earth”
(Passavant G., 2009). In fact, the first section of the appendix describes aviation gasoline as, “a complex
mixture of relatively volatile hydrocarbons that vary widely in their physical and chemical properties.
The engines and aircraft impose a variety of mechanical, physical, and chemical environments. The
properties of aviation gasoline (Table X1.1) must be properly balanced to give satisfactory engine
performance over an extremely wide range of conditions” (ASTM International, 2007). The specification
further alludes to the point that the fuels contained within this specification are defined the way they
are due to years of cooperative experience between fuel producers, aircraft companies, engine
companies, pipeline distributors, additive companies, the U.S. military, civilian aviation, and aviation
federal regulators. The specification reads that the requirements of the fuels listed in Table 1 are,
“quality limits established on the basis of the broad experience and close cooperation of producers of
aviation gasoline, manufacturers of aircraft engines, and users of both commodities” (ASTM
The next area of the appendix goes into great detail of how the antiknock quality (i.e. MON and supercharge) numbers have been derived and the importance of each of those numbers. Of late, Lycoming Engines has advocated the importance of a 100 octane fuel and the need for its continued existence. When posed a question in Lycoming’s recent fuels bulletin of using a sub-100 octane fuel, and whether it was really necessary to have a 100 MON fuel, a Lycoming representative responded with the following statement: “The bigger issue is that the aircraft that need 100 octane fuel to maintain their performance are also the aircraft that fly the most, use the most fuel, and access related aviation services most often. If these aircraft lose access to 100 octane and can no longer perform the missions for which they were intended, owners and operators may decide to remove them from service, decreasing demand for aviation grade fuel and aviation services” (Lycoming, 2010). Although there is much information in the public domain regarding the importance of a 100 MON fuel for aviation, and warning that general aviation’s future would be in question without 100 MON fuel; it is important to understand what the engine manufacturers have to say on the issue because they are the experts on what their engines require to run safely. This insight from Lycoming is important as Lycoming holds well over 70% of the general aviation piston engine market (Ian Walsh, 2008). The Lycoming position goes on to mention that if a 100 MON fuel does not come to market to replace 100LL, “expensive retrofits would likely fail to make up for the loss in octane. To make up for the lost revenue, providers of aviation goods and services would likely be forced to increase prices charged to those who remain in piston general aviation. In total, the economic cost to general aviation could be in the billions of dollars” (Lycoming, 2010). The key elements here are that the engines cannot be modified to make up for the loss of performance, and what modifications are added to restore some of the performance, would dramatically increase the cost of the goods and services provided by these aircraft.

This argument by Lycoming becomes even more relevant as the concept of carbon tax is discussed with relation to aircraft. As the octane ratings of aviation gasoline has been lowered over the
years, it has been generally assumed that turbine engines would gradually replace the high horsepower piston engines. As turbine engines became lighter and more affordable in the 300 hp to 1000 hp ranges, there seemed to be less need for piston engines in these ranges. However, turbine engines have been targeted as emitters of CO and CO2. The result of this is discussion around the world regarding imposing high taxes on turbine fuel. The purported purpose of these taxes is to force users to use less carbon intensive modes of travel. This then means that in the 300 to 1000 horsepower ranges there could well be no aircraft powerplants available. Those working aircraft that carry supplies to remote regions of the planet, perform humanitarian aid, and provide transport of people to places not served by heavy turbine powered aircraft, could find themselves parked for lack of fuel and no suitable replacement powerplants.

Beyond the explanation of octane numbers, the D910 specification explains why in particular TEL was chosen, and still in use. D910 explains that, “Tetraethyl lead offers the most economical means of providing high antiknock value for aviation gasoline. It is added to aviation gasoline in the form of a fluid which, in addition to tetraethyl lead, contains an organic halide scavenging agent and an identifying blue dye” (ASTM International, 2007). When aviation gasoline was developed, the discipline of organic chemistry (chemistry carbon based sources), was in its infancy. In-organic chemistry or chemistry involving atomic elements and non-hydrocarbon molecules was well established. When working with in-organic chemical compounds, it turns out that not only is tetraethyl lead the most economical solution to gasoline detonation, but maybe one of the only solutions. In the hunt for replacements for tetraethyl lead since the 1970’s there have been no promising replacements. And even as organic chemistry has developed into a better known science there have proven to be few alternatives. So the specification’s statement is in fact a dramatic understatement about why TEL is used.
With regard to the dyes, one might question as to why the need for aviation fuel to be dyed exists. The D910 states that by law all fuels “containing tetraethyllead must be dyed to denote the presence of the poisonous component. Colors are also used in aviation fuels to differentiate between grades” (ASTM International, 2007). The dye section also mentions that previous experience has shown that “only certain dyes and only certain amounts of dye can be tolerated without manifestation of induction system deposition” (ASTM International, 2007); this is the reason limits are listed for each dye in Table 1.

Density is mentioned briefly in the specification. Table 1 requires that the density is a reported value rather than within a range of values. In the Appendix, it mentions that density is important for fuel flow metering in aircraft fuel systems. The next item that is mentioned is the requirement for a Net Heat of Combustion value in Table 1. According to Table 1, the Net Heat of Combustion has a value listed as the minimum a fuel should read. The specification continues to state that this is an important parameter because this value “provides a knowledge of the amount of energy obtainable from a given fuel for the performance of useful work, in this instance, power. Aircraft design and operation are dependent upon the availability of a certain predetermined minimum amount of energy as heat” (ASTM International, 2007). If this minimum value is violated in a fuel sample, would result in an increase of overall fuel consumption noticed by the pilot and a subsequent loss in range. In fact all aviation gasoline has the same heat/energy content regardless of the octane rating. Just as with automobile gasoline, a higher octane rating does not indicate more heat or more energy in the fuel. The popular myth that high octane engines contain more heat, or energy, probably comes from the common knowledge that higher horsepower engines use high octane fuel. People assume that it is the high octane fuel that provides the engine’s power, when in fact it is the design of the engine that produces high horsepower, and the high octane fuel simply allows the engine to run properly.
There are two methods used in the current D910 to obtain this measurement of heat content, a direct measurement method, and an estimation method. The estimation is used with current 100LL because the parameters of gasoline are well known; however, with future unleaded fuels, the estimation method is not as reliable. Therefore, the direct measurement method afforded by ASTM D4529 is preferred by ASTM. The section concludes that “No great variation in density or heat of combustion occurs in modern aviation gasolines, since they depend on hydrocarbon composition that is already closely controlled by other specification properties” (ASTM International, 2007). This line of thought is surely to change as new fuels which are outside of the box of current D910 fuels comes to the forefront of fuels. The new specifications which govern these new fuels have been edited to account for these eventual changes.

The next major area of the appendix discusses fuel volatility. According to its definition, volatility is “the property of changing readily from a solid or liquid to a vapor” (Merriam-Webster, 2011). When relating to aviation gasoline, volatility means a couple different things. The specification specifically breaks volatility into two separate sections including vapor pressure and distillation. The first area explained in detail as vapor pressure. As compared automobile gasoline, avgas has a much narrower band of vapor pressure. Vapor pressure in general refers to the fuels ability to vaporize or evaporate. In aviation vapor pressure is important because of vapor locking tendencies with fuels that are above the upper end of the vapor pressure range listed in D910. Vapor lock is when the liquid fuel turns from a liquid to a gas, or vapor, somewhere in the fuel system of the aircraft before the fuel gets to the engine cylinders. When fuel “vapor locks” the supply of fuel to the engine is interrupted and the engine stops. Controlling the vapor pressure of aviation gasoline is important and difficult since the engines go to high altitudes. The low atmospheric pressure at high altitude can facilitate unwanted fuel vaporization, or vapor lock. This section of the specification refers the reader to a research report discussing in great
detail the lessons learned by the ASTM subcommittee regarding vapor pressure, and how these lessons pertain to aviation.

The next important section covered under the volatility section is distillation. When examining alternative fuels, which are different in composition than current 100LL, distillation is where a person notices variations from the D910 standard. This section of the specification explains the importance of each one of the parameters of listed in Table 1. In its broadest form, the percents listed in Table 1 under distillation represent the percents at which the corresponding value of the sample being distilled has evaporated. For example, the first percent that is listed is 10% volume evaporated. The number the report is asking for is a temperature in degrees centigrade. Listed in D910 is the maximum temperature that an acceptable sample can reach at 10% evaporated (distilled). According to D910 the reason that a maximum of 75° C was set for 10% is to, “ensure ease of starting and a reasonable degree of flexibility during the warm-up period” (ASTM International, 2007). One then notices reading the appendix that the subcommittee explained why there was a minimum of 75° C established in the D910 at the 40% volume range. The specification explains that this minimum value was included “in an effort to control, indirectly, specific gravity and, consequently, carburetor metering characteristics” (ASTM International, 2007). Continuing on down the distillation curve, the next specified point is the 50% volume evaporated maximum temperature. The specification indicates that this temperature shall be no more than 105° C. In the discussion contained in the appendix the subcommittee explains the reason this value was added was “to ensure average volatility sufficient to permit adequate evaporation of the fuel in the engine induction system. Insufficient evaporation may lead to loss of power” (ASTM International, 2007). One of the last specified volumes contained within the distillation curve is the 90% volume distilled point. The specification indicates that this temperature shall not exceed 135° C. This was done in an attempt to “prevent too much liquid fuel being delivered to the cylinders, resulting in power loss, and to prevent poor distribution to the various cylinders” (ASTM International, 2007). If the following condition was
present the fear is that some individual cylinders may become extremely lean. The pilot would notice the propagation of this situation “with consequent engine roughness, perhaps accompanied by knocking and damage to the engine.” The committee also goes on to mention that “Lowered fuel economy and excessive dilution of the lubricating oil may result from too high a 90 % evaporated point” (ASTM International, 2007).

Surrounding the individual percents contained within the specification, there exists the initial boiling point of the fuel, which is a reported value rather than a maximum or minimum. A final boiling point is specified to be at a maximum of 170° C. The initial and final boiling points most directly translate to operational considerations. The initial boiling point is reported as the temperature at which the initial drop of the test sample evaporates. This value is most closely related operationally with the ease of a given fuels ability to vaporize during a cold start of an aircraft engine. Even though there is no direct maximum or minimum applied to initial boiling point one can determine that it must occur before 75° C; this is because by 75° C, at least 10% of the volume must be evaporated. With regard however to the final boiling point, the maximum prescribed by D910 is 170° C. The rationale for this specification parameter indicates the fuels ability to hot start an aircraft engine. The committee explains that the reason a maximum value was cited for the final boiling point (also known as the end point) along with a maximum for the 90% evaporated point was to, “prevent incorporation of excessively high boiling components in the fuel that may lead to maldistribution, spark plug fouling, power loss, lowered fuel economy, and lubricating oil dilution” (ASTM International, 2007). Basically what the committee was saying was that a fuel manufacturer could keep hot fuel from boiling by adding lots of heavy hydrocarbon compounds. These heavy compounds might not burn well and would cause problems in the engine. In order to limit how much of these heavy compounds the fuel manufacturer can “dump” into the gasoline to keep the hot fuel from boiling. Ideally an alternative to 100LL would mirror the distillation curve contained within D910; however, with the emerging alternatives this is proving not to
be the case. This is because the parameters in the specification have been created around the physical properties and reactions of hydrocarbon based gasoline. Alternative fuels may well not behave the same way as gasoline. Therefore, if for example, an alternative did not meet the 90% point in the distillation curve the items mentioned above of “maldistribution, spark plug fouling, power loss, lowered fuel economy, and lubricating oil dilution” would all have to prove via test data that they were unaffected by the alternative fuel. All of the above mentioned items are what is considered the core of the distillation curve; however, there are some other lingering variables based off of the distillation numbers which are specified in D910. They are: sum of 10% + 50% evaporated temperatures, recovery volume, residue volume, and loss volume. The first test is somewhat self explanatory, the 10% value is added to the 50% value and the temperature is reported. The sum of these temperatures must be greater than 135° C. The reason this item was added into D910 Table 1, according to the subcommittee, this value was included “To guard against too high a volatility that might lead to carburetor icing or vapor lock, or both” (ASTM International, 2007). With regard to the other items of the distillation curve included in D910, the committee explains that, “The stipulation of a minimum recovery and a maximum loss in this specification in conjunction with the vapor pressure requirement is intended to protect against excessive losses by evaporation in storage, handling, and in the aircraft tank. It is also a check on the distillation test technique” (ASTM International, 2007). These subtleties in determining the parameters is the result of decades of experience that should not be ignored when designing the next generation of unleaded aviation gasolines. The last and final distillation value discussed is the requirement not to exceed a maximum value of 1.5% residue volume. Residue volume is what is left over that could not evaporate during the distillation test. The committee explains that the reason they put this maximum value in D910 was to “prevent the inclusion of undesirable high-boiling components essentially impossible to burn in the combustion chamber, the presence of which may reflect the degree of care with which the product is refined or handled.” The committee also goes on to summarize that
the amount of residue remaining after distillation when combined with the end point temperature data can be used as a measure of fuel contamination with undesirable “high-boiling materials” (ASTM International, 2007).

Another parameter which is listed in Table 1 is a maximum freezing point. The temperature listed in Table 1 is -58° C. This parameter is included in D910 to ensure that any fuel that is considered avgas does not begin to freeze at altitude while an aircraft is in flight. This would obviously disrupt the fluidity of the fuel and its ability to effectively flow through the fuel system of the aircraft. The subcommittee also mentions that a fuel system icing inhibitor may be added to aviation gasoline. Specifically, the subcommittee mentions that “Isopropyl alcohol (IPA), approved in 6.3.2.1, and diethyleneglycol monomethyl ether (Di-EGME), approved in 6.3.2.2” (ASTM International, 2007), are acceptable fuel system icing inhibitors under D910. Also discussed in this section of the appendix are the potential corrosion of fuel system and engine parts. Two tests are included in the D910 Table 1 that pertain to corrosion characteristics of the fuel. The first test, the copper strip test, requires that the fuel pass the immersion of a copper strip in a sample of fuel. This test “provides assurance that the product will not corrode the metal parts of the fuel systems” (ASTM International, 2007). The second corrosion test of sulfur by mass percent aims to measure the total sulfur content of the tested aviation fuel. This test is “significant because the products of combustion of sulfur can cause corrosive wear of engine parts” (ASTM International, 2007).

The last major section of explanation of Table 1 pertains to fuel cleanliness & handling and storage stability. Explained in this section are the oxidation stability parameters of potential gum and lead precipitate. Commonly, after fuel sold from the fixed-base operator at an airport (FBO), it is not all used immediately. Routinely pilots return to the airport with some fuel left over in the aircraft’s tanks. It can then be a matter of weeks or months until the pilot returns to fly the aircraft. During this elapsed
time, aircraft and the hangars they are stored in can experience a variety of different climates and
temperatures. The potential gum test contained in Table 1 of D910 is aimed to address this scenario, to
ensure viability of the avgas after it leaves the FBO. According to the explanation afforded by the
subcommittee in the appendix, “The potential gum test, which is an accelerated oxidation method, is
used to estimate fuel stability in storage and the effectiveness of oxidation inhibitors. If the fuel is to be
stored under relatively mild conditions for short periods, an oxidation period of 5 h is generally
considered sufficient to indicate if the desired stability has been obtained, whereas a 16-h period is
desirable to provide stability assurance for long periods and severe conditions, such as storage in
tropical climates” (ASTM International, 2007). In Table 1, a minimum of 5 hours of testing is required;
however, there is a footnote that allows for a 16 hour test period. The other oxidation parameter
explained by the appendix is visible lead precipitate. This test attempts to identify a maximum
parameter for insoluble lead (lead precipitate). “The formation of a lead precipitate during the aging
period of the potential gum test under the accelerated oxidation conditions used in this determination
indicates a potential instability” (ASTM International, 2007). This test is vital to the long-term storage
capability of the avgas. Even the tiniest amount of insoluble lead or foreign material could lead to
plugging or fouling of fuel system filters and spark plugs causing difficulty in operation of the engine.
The committee explains that they felt it was “necessary to place a limit on the amount of precipitate
formed in this determination” (ASTM International, 2007). Even though this parameter exists, not all
tests for gum or particulates are perfect. Recently multiple independent ASTM certified laboratories
have found that fuel meeting ASTM D910, when stored for periods of up to three weeks after purchase
from the FBO, had visible lead precipitate in the tested samples. It was postulated by the experimenters
that this was due to refiners modifying the formulation of their aviation gasoline in an attempt to
stretch the supply of high quality petroleum blend-stocks. The samples met the requirements of D910,
including the lead precipitate maximum, and still had visible lead particulate in the sample after it was
aged for up to a month. This lends credence to the fact that specifications are a good measure of how a fuel sample performs, however they are not 100% perfect.

Mentioned in the appendix, the water reaction volume change test and electrical conductivity tests are explained. The subcommittee explains that with regard to the water reaction test, it “provides a means of determining the presence of materials readily extractable by water or having a tendency to absorb water.” The committee also mentions that “When the fuel consists essentially of hydrocarbon components, there is no measurable change in the volume of the water layer” (ASTM International, 2007). This is in the specification to make sure that there are no chemicals in the fuel that can absorb water. Absorbing water can lead to ice crystals in the fuel, or can cause the water to massively fall out of the fuel when it is shock cooled. This leads one to believe that any future unleaded replacement for 100LL should contain hydrocarbon components.

Another major test mentioned is the electrical conductivity test. This test attempts to address the concern between static electricity and avgas. A pilot might notice that when the aircraft fuel tanks are filled by the FBO, that a static grounding line is first connected to his aircraft there by grounding the aircraft and the fuel truck to the ground. This is done in an attempt to control static electricity that can build up due to fueling aircraft fuel tanks. The electrical conductivity test contained in Table 1 is meant to mitigate problems that exist in the handling of aviation gasoline. The appendix explains that “Addition of a conductivity improver may be used as an additional precaution to reduce the amount of static electrical charge present during fuel handling” (ASTM International, 2007). A footnote to this test in Table 1 indicates that this test should only be performed “when electrical conductivity additive is used” (ASTM International, 2007).

A brief statement is also made, in this section, pertaining to microbial contamination. This has been a concern over the recent years and the subcommittee states that, “Uncontrolled microbial
contamination in fuel systems may cause or contribute to a variety of problems including corrosion, odor, filter plugging, decreased stability, and deterioration of fuel/water separation characteristics. In addition to system component damage, off-specification fuel can result” (ASTM International, 2007). Despite this, there exists no standard test or specification for microbial contamination in ASTM D910’s Table 1. The appendix references ASTM D6469 as a guide to microbial contamination; however, as mentioned before there is no limitation contained in D910 pertaining to aviation gasoline and microbial growth.

The last section in ASTM D910 pertains to aromatics content. Aromatics are defined as, “Hydrocarbons derived from petroleum, characterized by a ring-like molecular structure and 'sweet' or aromatic odor. Benzene, toluene, and xylene are the most common aromatics, and are used as chemical feedstocks, solvents, and as additives to gasoline to raise its octane rating” (BusinessDictionary.com, 2010). This section is a more recent addition to D910’s appendix. The reason this section has been added is that aromatics are understood “to affect elastomers to a greater extent than other components in aviation gasoline” (ASTM International, 2007). Elastomers are the flexible materials usually used in gaskets, seals, and other flexible sealing materials. Many people still refer to these seals as being made of “rubber” even though seals have not been made with real rubber for decades. Too much aromatic content can swell or break down the sealing materials. Too little aromatic material is thought by some engineers to prevent proper sealing. This section goes on to mention how a high amount aromatics in the avgas could be ruled out of inclusion in the specification by certain parameters it does mention that there is no maximum aromatic limit associated with ASTM D910. However, based on experience, the subcommittee believes it very unlikely that total aromatic content could be above 25%.

The specification D910 as a whole is very inclusive with explanations for each individual requirement contained within the specification; however, the specification is not perfect, it merely
serves as guidance based on years of experience. As incidents and problems arise, D910 and other aviation gasoline specifications can be modified to mitigate those risks in the future. This is the reason all ASTM specifications come up for renewal every two years. No matter what the future fuel for general aviation may be, everyone that comes in contact with that fuel will more than likely be beholden to an ASTM specification. Without a governing specification that is rooted in industry-based consensus, safety is clearly compromised.
When examining common thought of alternative fuels, especially one that might be used to replace 100LL for general aviation, one alternative that is commonly mentioned is ethanol. With regard to motor fuels, mixing ethyl alcohol with petroleum derived gasoline is not a new concept. Some of this nation’s first vehicles, like the model T Ford, were designed to run on either petroleum gasoline or alcohol. In 1925, Henry Ford - founder of the Ford Motor Car Company, told a New York Times reporter that, “ethyl alcohol was the fuel of the future,” he went even one step farther to say “The fuel of the future is going to come from fruit like that sumac out by the road, or from apples, weeds, sawdust -- almost anything," he said. "There is fuel in every bit of vegetable matter that can be fermented. There's enough alcohol in one year's yield of an acre of potatoes to drive the machinery necessary to cultivate the fields for a hundred years” (Ford Predicts Fuel from Vegetation, 1925). According to the history presented on the Ford Motor car company web site, Henry Ford even built a mini-ethanol production facility, but closed it as petroleum gasoline gained popularity.

In fact photos, such as the one below named Figure1, and articles dating from the early 1930’s show gas stations advertising corn-derived alcohol blended gasoline. Though at the time this seemed to be a novelty not intended for mainstream use due to the lack a sufficient production.
With the Arab Oil Embargo in the early 1970s, America experienced a newfound interest in using ethanol as a motor fuel. In the 1970s corn alcohol blended with gasoline became known as, gasohol. This was in an attempt to put a different marketing spin on an old product. The use of gasohol began to break into small stock car and off-road racing circuits. Racers enjoyed using this fuel as it provided a higher motor octane number and anti-detonation characteristics than that of the fuel they were using at the time. Ethanol was shown to raise the motor octane number (MON) by as much as 2 to 4 points. Even though ethanol was available to racers and specialty car owners, gasohol was not yet widely produced. This was due to the fact that the majority of the production of alcohol in the United States was meant for human consumption as alcoholic beverages, rather than an enhancer to gasoline.

Ethanol can be produced from a variety of different manufacturing processes; however, there are two main methods of ethanol production, petro-chemically or fermentation. When ethanol is used as an industrial feedstock or solvent, the ethylene hydration process is used for production. “Ethylene is hydrated and catalytically reacted on a phosphoric acid absorbed catalyst to produce ethanol” (Encyclopedia of Chemical Technology, 1991). This form of ethanol is referred to as synthetic ethanol.

The other more popular form of ethanol production which is used is fermentation. This method of ethanol production is relatively the same whether the ethanol is used for alcoholic beverages or for fuel. Unlike the ethylene hydration method of ethanol manufacture, fermentation is not petro-chemically derived. Rather, sugars from biomass materials (such as corn) are fermented to produce ethanol. Many large scale ethanol facilities currently use this technology; whereby, the yeast is used to metabolize the sugar during the fermentation process to produce ethanol and carbon dioxide (CO$_2$). The result and product of this fermentation is what is referred to as a beer mix. The beer mix “will contain about 10% alcohol, as well as all the non-fermentable solids from the corn and the yeast cells (McIntyre, 2003). The quality of ethanol which is produced out of this fermentation process is not yet at the purity required to be added to gasoline as fuel, as it must first be distilled to increase the purity or the proof of the
ethanol. The distillation process takes the roughly 10% alcohol by volume (ABV) beer mix and heats it to separate the ethanol from the other components of the beer mix such as water and other chemicals.

Once the beer mix it is distilled, bio-refiners are left with a much higher purity ethanol. The product exiting the distillation columns, also known as the rectifier and stripper, “is increased from 45% to 91% by weight” (McIntyre, 2003). This equates to roughly a 190 proof ethanol. Though this is much higher than the beer mix that went into the distillation column, it is not quite finished. Bio-refiners have a manufacturing goal of a 200 proof ethanol. To achieve the additional 10% ABV concentration of the ethanol, “The concentrated vapor from the rectifier is superheated and passes through one of two dehydrating molecular sieve beds; one is used while the other is regenerated. Vapors from the regenerated bed are condensed and recycled to the rectifier. The superheated vapor passing through the molecular sieve bed contains more than 99% by weight anhydrous ethanol” (McIntyre, 2003).

This distillation process requires a lot of heat and energy to separate the alcohol from the other byproducts. In fact, this process has given ethanol plants their signature steam plume, which is now associated with bio-ethanol refineries. Some people claim that anywhere from four to six times the amount of energy that is gained from one gallon of ethanol goes into its production. This is because of the high temperatures that these distillation columns require. Nonetheless, domestically produced fuels may still the wave of the future. First generation bio-fuels, such as ethanol, may be a step in the right direction; however, much more work is needed for sustainable domestically produced fuel.

If ethanol is to be used in aviation as a replacement for 100 LL, one place to begin is by examining the research information that is available, since automobiles have been running on ethanol for over 80 years, allowing for several studies of the effects. With a quick examination of the literature available, several researchers have addressed ethanol as a replacement fuel and the need for it in the marketplace.
It is widely known among those knowledgeable about aviation history that the V-12 Rolls Royce engines used in the Hawker Hurricanes, used in the Battle of Britain in WWII were powered by alcohol. Unfortunately there are few if any records kept of this since those were desperate and chaotic times in British history. Basically in those days the British put anything in the aircraft that would burn. It is only commonly known that alcohol fuel was used by the British during the Battle of Brittan since the fuel accounted for the majority of the massive burns received by British pilots when the aircraft was shot down. Since the alcohol flames were nearly invisible the pilots did not realize they were on fire. So without published data from this period of WWII all that remains were automotive related information.

Even though none of the articles found were applicable to aviation directly, the information is pertinent. One such article by Varde, Jones, Knutsen, Mertz, and Yu (2007) discussed the fact that alcohol fuels have been used for decades, but it is only recently that they have been considered for use in automobiles. It is discussed further that ethanol’s popularity is increasing with many public and legislative-minded people because it is completely biodegradable and renewable (George, Schroeder, and Xie, 2005). Varde et al. (2007), George et al. (2005), and Hill (2003) all are quick to point out that ethanol has proven consistently a reduction in overall emissions [per gallon, not per mile] as compared to conventional gasoline as the following quote explains, “there were consistent reductions in NO\textsubscript{X} levels, particularly with the E-85 blend” (Varde et al., 2007, p. 933). It is also mentioned by Varde et al. (2007) that, “E-85 produced somewhat lower HC [hydrocarbon] levels than those produced by gasoline” (p. 941). This makes the argument for ethanol’s use in aircraft as a means to reduce pollution.

Countering this argument; however, George et al. found that, “The potential for electrochemical corrosion in the piston powered general aviation fleet was examined for the various gasoline-ethanol blends that have been proposed in the presence of moisture (water)” (p. 8551). Water in aviation fuel was also examined by Hill in which it was stated that, “a range of microbes (microorganisms), in the
classes of bacteria, yeasts and moulds, can all flourish in wet [hydrous] aviation fuel at all distribution and use” (p. 497). Hill goes on to mention that with the introduction of microbes into an aircraft engine, serious damage, possibly stoppage of engine could occur. Although Varde et al. (2007), George et al. (2005), and Hill (2003) all discussed the many benefits as well as shortcomings of using ethanol; standing alone was Varde et al. (2007) who failed to mention any major downside to the use of this fuel relating to water content. Nevertheless, Varde et al. (2007) and George et al. (2005) both mention that ethanol is a step in the right direction; it is only George et al. (2005) that believes it is inappropriate for use in aviation.

Despite however what the experts said, ethanol has been used in a rather extensive research project by South Dakota State University to power general aviation aircraft. The South Dakota researchers called their product aviation grade ethanol 85 (AGE 85). The project was aimed at designing and ethanol based fuel to replace 100LL. This went above and beyond the typical E-95 (95% ethanol & 5% Avgas) or E-100 blend ethanol used on highly modified piston aircraft engines. Feats such as these have been accomplished by such air show acts as the Fagen Ethanol Corporation and the Vanguard Squadron. AGE85 was originally designed to be compatible with existing aircraft and the existing 100LL fuel supply chain. The composition of “Aviation-grade E85 refers to a reciprocating-engine aviation fuel that contains about 85 volume percent (vol%) ethanol and about 15 vol% “pentane isomerate” (an oil refinery product comprising about 35 vol% isopentane), in addition to small amounts of soy methyl ester lubricant and a fatty acid-based corrosion inhibitor” (Behnken, Helder, & Johnson, 1999). It was also noted by the research director that the percent by volume (vol%) of ethanol contained within the end product had a range of 80 to 90% to meet fuel volatility requirements depending on the season of year. According to a gas chromatograph trace the pentane isomerate contained mostly isopentane (53%). Other major components in the pentane isomerate included: isohexane (23%), dimethyl butanes (11%),
cyclohexane (5%), & n-pentane (4%). There were also trace amounts of: isobutene, n-butane, & n-hexane.

The researchers made it very clear that they were interested in shifting the paradigm from modifying engines and airframes to work on alcohol to designing an ethanol based fuel for general aviation, and then make any necessary modifications to the engine the airframes after. There were, however, some major issues with AGE85, which disqualified it as a drop-in replacement fuel. The first major issue that AGE85 had to tackle was that ethanol by itself has an inherently low vapor pressure. As we discussed earlier, vapor pressure is one of the cornerstones of aviation gasoline, the designers and OEMs have used a model engines after. The low vapor pressure could cause the fuel to vaporize in the fuel system, before it reached the engine cylinders, and cause the flow of fuel to the engine to stop.

The established industry standard could not be violated by any alternative to 100LL. AGE85 researchers attempted to solve this problem by allowing their fuel to be blended with pentane isomerate the control the vapor pressure. This was the same tactic used by E-85 producers to boost vapor pressure for combustion in an automobile engine. One added benefit of this addition to the mixture increases flame visibility when burned, so that way when a sample was burned in the open, the flame would appear much the same as 100LL does, thus making the fuel safer in the event of a fire.

Another problem faced in the past by those that have attempted to use ethanol for an aviation fuel is the possible corrosion that occurs when the engine is stored (i.e. in a hangar between flights). The alcohol by definition is hydroscopic, which means that it absorbs water. This water can cause corrosion where the water comes in contact with parts that will corrode. The designers of AGE85 proposed that biodiesel, known as B-100, be blended in small amounts in hopes that the oil in the biodiesel would protect the exposed surfaces of the engine. The researchers claimed that this would add protection for all fuel-wetted components (Helder, 2000).
Since biodiesel in this country comes primarily from soybean oil, known as methyl-ester soyate, there exists all whole new set of problems in its use as a blending additive for aviation. A problem with biodiesel is that each batch is inherently different. Factors such as agricultural field where it is grown and time of year harvested all can drastically change the final composition of the B-100 biodiesel. Even two fields directly across the street from each other, planted with the exact same soy bean seed, can yield two different compositions of biodiesel. The researchers claimed that AGE85 would contain no more than 1% by volume of B-100 biodiesel, but because a consistent end-product could not be guaranteed, using such a product, even as an additive for aviation, became impractical.

When compared with 100LL’s Table 1 properties from a ASTM D910, AGE85 raised up some immediate red flags. Though the motor octane number of 106 and no tetra-ethyl lead seemed appealing, the Reid vapor pressure was out of the margin provided by D910. AGE85 exhibited a vapor pressure of 6.5 PSI to 8.0 PS I (Helder, 2000). This was nearly 1PSI higher than that of 100LL (5.5-7.1). Another parameter that seemed to be a critical area of concern was the minimum net heat of combustion. Net heat of combustion was an indication of the power provided by each gallon of fuel as it was combusted. 100LL had an established minimum of 112,200 BTU/ gallon; whereas, AGE85 registered as 88,200 BTU/gallon. This was far below the minimum established by 100LL. This would directly correlate in a significant loss of a range per gallon by the pilot. If not known and accounted for ahead of time during pre flight planning by the pilot, he might not make it to the destination before running out of fuel. Another area of concern is that AGE85 weighs anywhere from 6.3 to 6.5 pounds per gallon. At first blush this might seem significant as pilots know 100LL as having a density of 6.0 pounds per gallon. Since 100LL does not have a fixed a recipe, its density will fluctuate from less than 6.0 pounds per gallon to just over 6.5 pounds per gallon; putting AGE85 right in that range. Nonetheless this potential weight change must be accounted for due to the significantly reduced net heat of combustion of AGE85.
To mitigate range and energy concerns, the researchers in charge of AGE85 suggested that the fuel system flow capacity be increased by 20%. They claimed that, “Typical aircraft systems allow 12:1 air/fuel ratio at full rich [fuel setting],” an “Increase in fuel flow capacity to allow 10:1 air/fuel ratio on AGE85 [should fix the problem]” (Helder, 2000). This would require extensive modifications to the current fleet which uses 100LL. Once a change was made to accommodate the 10:1 air to fuel ratio the aircraft would not be backwards compatible with 100LL.

The other proposed solution by the South Dakota researchers was to operate the aircraft with the propeller operating at a higher blade pitch. On aircraft with propellers of adjustable pitch, operating the propeller at a higher pitch allows the propeller to take a larger “bite” out of the air on each revolution. This technique is similar to operating a car in a higher gear. The vehicle can go further on each turn of the engine, however it takes more power to turn the propeller. The South Dakota researchers planned to exploit the high octane number of the AGE 85 to allow it to generate the extra power. This technique worked on some aircraft, but not all aircraft had variable pitch propellers, and all aircraft needed to operate in low propeller pitch (low gear) for takeoff and climb.

The retrofit of the aircraft fuel systems to accommodate higher fuel flows provided a major logistical hurdle which more than likely could not be overcome with our single source distribution system that delivers aviation gasoline throughout the United States. Aside from the air/fuel ratio issues, material compatibility was a concern when using an ethanol based fuel. The researchers began to explore how materials might react with AGE85. They briefly noted that, “Metal components have shown no corrosion in over three years and most polymer materials used in aviation the past 15 years are alcohol compatible” (Helder, 2000). With regard to the metal components researchers added that B-100 biodiesel afforded additional protection against corrosion or degradation.
Material compatibility of any alternative fuel most directly affects polymer materials that are located in the fuel system. While it may be true that over the past 15 years alcohol compatible polymers have been used in aviation fuel systems, our current fleet flying on 100LL dates much farther back than 15 years with fuel system components that we’re designed 40 or 50 years ago. For these aircraft AGE85 might not be compatible; however, further testing would have to be accomplished in order to determine compatibility. In an attempt to reduce negative criticism the researchers stated the following, “In comparison to toluene in 100LL, ethanol and Biodiesel may prolong the life of fuel bladders and fuel system components” (Behnken, Helder, & Johnson, 1999).

Several flight tests were performed on AGE 85. The aircraft used were based at South Dakota State University. They included a 1962 Cessna 180, a Mooney 201, and a radial engine AeroTractor to name a few. Several tests were performed both on the ground and in the air to prove AGE85’s compatibility with these aircraft. The bulk of the testing was conducted on the Cessna 182. Tests were focused on engine performance specifically power output and durability. A 500 hour test was performed on the engine including such tests as cool and hot climb, in flight engine restarts, and detonation mapping. All of these tests indicated that the fuel performed equivalently to 100LL.

Corrosion and lubricity tests were conducted in the laboratory where 100LL was used as a baseline for measurement. The corrosion test was not performed using the ASTM standard, rather an SAE test method was used. This test immersed samples of aluminum alloy into samples of both 100LL and AGE85. Two representative 100LL samples were used for accuracy. Based on the test results shown, the rate of weight loss (µg) of each alloy was less in AGE85 than in each of the 100LL samples (Behnken, Helder, & Johnson, 1999). The problem with this test data however, was that a blend was not specified for the AGE85 that was used to conduct the test. So, one does not know, how much B-100 biodiesel was in the mix or what percent volume ethanol was used in the final mix. Information on
lubricity of AGE85 was also presented via the Ball on Cylinder Lubricity Evaluation (BOCLE). This is ASTM D5001 and is meant to evaluate lubricity of jet turbine fuel.

This test involves a ball and cylinder which are agitated to gather, in a constant motion, using a sample of fuel between them as lubricant. At the conclusion of the time prescribed in ASTM D5001, the wear-scar is measured in millimeters. Since there exists no lubricity standard in D910 for aviation gasoline, D5001 is used by the industry as the unofficial lubricity standard to indicate the viscosity of a particular alternative fuel. The one flaw in using this test is that due to the high a volatility of 100LL, sampling it by using the D5001 test can prove to be too sporadic to get an accurate reading. In the test provided by the researchers of AGE85, they indicated that 100LL was 0.79mm and AGE85 was less with 0.53mm (Behnken, Helder, & Johnson, 1999). The data table for this test is provided in Figure 2 below.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Sample</th>
<th>Wear Scar Dia. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2876</td>
<td>AGE-85</td>
<td>0.53</td>
</tr>
<tr>
<td>2877</td>
<td>100LL</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Figure 3 - ASTM D5001 Test Results

Providing the figures for 100LL are accurate, this test indicates that AGE85 provides appropriate lubrication more so than 100LL.

The end result of the AGE85 project was that in a slightly modified Cessna 180 & 182 it seemed to work without fault. Based on all the data that was presented to the industry the C-180 & C-182 was issued a supplemental type certificate (STC) to run on AGE85. In addition to this work, dual fuel STC’s were also issued to the AGE85 research team. This allowed for AGE85 and 100LL to be blended in any ratio together in these STC’d aircraft (Helder, 2000). In a presentation to the ASTM subcommittee for aviation fuels in late 2005 researchers indicated that they would like to focus their efforts on small radial engines.
To date however, none of that work has been presented in public. The production of AGE85 on a small or large scale is nonexistent commercially. Only small micro batches of a drum at a time have ever been produced.

The future of AGE85 as an unleaded replacement for avgas is very unclear. As of the last presentation to the ASTM subcommittee, AGE85 researchers indicated they were not going to attempt ASTM certification of their product for commercial manufacture and sale. In late 2006, the web site owned by the research group which was home to the AGE85 project, www.age85.org, was de-registered. Web presence of the AGE85 project is very few and far between and hard to locate. E-mail addresses return as disconnected, and the researchers have not been present at the ASTM since their last appearance in late 2005. Based on all of these factors and AGE85’s small area of focus, it is unlikely that AGE85 is a suitable candidate for the replacement of 100LL aviation gasoline.
Chapter # 4

Hjelmco Oil – Unleaded Alternatives

While exploring aviation fuels it is hard to ignore Hjelmco Oil in Sweden. Hjelmco Oil, founded by Lars Hjelmberg in 1981, is fully owned by the Hjelmberg family (Hjelmco Oil AB, 2011).

According to Lars, the company was founded with a small amount of seed money given to him by his mother. At that time, Lars was working in the biomedical industry and flying as a private pilot. Lars began to wonder why the price of avgas was so expensive to buy and why the supply seemed to be very inconsistent. What he learned was that the fuel his fellow Swedish pilots were using came from refineries located in, what was at that time, the Soviet Union. The logistics became a nightmare in transporting this fuel from the Soviet Union to Scandinavia. With the problems identified, Lars began Hjelmco with the intent of moving production from the Soviet Union to Sweden in order to manufacture a more cost effective avgas that did not have such an extensive logistics chain from the refinery to the airport. At the time he entered the market, there were only two aviation fuel distributors in Sweden, Total and Shell. Hjelmco Oil became the third. The market remained the same three companies from then until now.

As the company rapidly progressed, and Hjelmco began making a name for itself in the aviation fuels business, Lars began working on some proprietary fuel blends, which he felt could easily work in current aircraft. According to the Hjelmco Oil website, in 1981, Hjelmco petroleum engineers began by launching what they considered the first generation of Hjelmco fuels, with their introduction of Hjelmco 80/87. This fuel was used in applications that did not require a high octane fuel such as 100LL. This fuel was somewhat covered by the ASTM D910 standard under the Grade 80 avgas standard. If the D910 standard was taken at face value, “If mutually agreed upon between the purchaser and the supplier,
Grade 80 may be required to be free of tetraethyl lead. In such case, the fuel shall not contain any dye and the color as determined in accordance with ASTM Method D 156,” (ASTM International, 2007) Hjelmco’s 80/87 was in compliance with ASTM D910.

Because the ASTM is primarily a U.S. standard there is no legal requirement that non-U.S. companies and countries follow the ASTM specifications. As long as the aircraft and engine manufacturers are comfortable with the fuel, and agree that it is equivalent to a D910 specification, that fuel can be used in aircraft around the world and will be supported by the aircraft and engine manufacturers. It does, however, improve the compatibility of aircraft, engines, and fuels, if a non-U.S. fuel producer follows the D-910 as closely as possible, and so the ASTM D-910 specification tends to be the target model for gasoline development worldwide. Because of this need for international compatibility Lars Hjelmberg, representing Hjelmco Oil, participated as a member of the ASTM committees for aviation gasoline beginning in the 1980’s.

There were however concerns among the ASTM committee members with the Hjelmco fuel fitting into the Grade 80 standard under D910, because the fuel contained components that were not originally included in the original Grade 80 fuel as it was originally certified under D910. Controversy aside, the fuel was used in Sweden under the aegis of D910 compliance between 1981 and 1991. The fuel was distributed to more than 50 airports nationwide in Sweden, and used by more than 400 aircraft, including the Royal Swedish Air Force, during that time period (Hjelmberg, 2004). During the time that 80/87 was distributed by Hjelmco, it was observed and reported by the company that no problems with the engine valves were observed. (Remember that engine valves were long considered to need lead for lubrication and cooling.) The company engineers even went on to claim that the time between overhaul (TBO) was improved by using this unleaded fuel (Hjelmberg, 2004).
The company also reported that if there was a disadvantage to this fuel being used, it was due to the fact that pilots tended to run their engines too rich. Hjelmco also acknowledged that some engines did need lead during the engine’s initial break-in period. The company engineers proposed that the solution to this problem would be to use regular 100LL avgas during the break-in period. This did indeed solve the immediate engine break in problem; however, this would not have been feasible in a totally unleaded avgas environment where there would be no leaded fuel at all. A replacement fuel for 100LL would have to replace all of the needs that 100LL had. Having a secondary fuel for engine break-in only, was impractical since the pilot would need to have had break-in fuels available at all potential airports to where the aircraft would be flying during the 25 to 50 hours of engine operation following engine overhaul.

Since the Hjelmco fuels are proprietary, little is known of the exact compositions; however, the details that are known is that the fuels potentially contained Ethyl tert-butyl ether (ETBE). ETBE is an oxygenate blended into fuels such as gasoline. The term “oxygenate” refers to the fact that the ETBE carries extra oxygen in the chemical, so when an oxygenate such as liquid ETBE is mixed with fuel the ETBE brings more oxygen to combine with the hydrocarbons in the gasoline. The result is typically a cleaner burning fuel. Many people familiar with high performance cars have heard of nitrous-oxide. Nitrous oxide is a gas, rather than a liquid, and is also an oxygenate, however its purpose is to add more oxygen to the combustion process in the engine cylinders to greatly increase engine power.

ETBE is commonly used in Europe as an oxygenate additive in gasoline blends to improve air quality; however, ETBE is very unpopular in the United States. The reason that ETBE has not caught on in the United States is that it is purported to seep into ground water. In places such as California where ETBE was tested as a method of reducing vehicle air pollution, evidence was cited of ETBE appearing in the ground water. And unfortunately ETBE is difficult, if not impossible, to filter out of the water. While
the same can be said for many of the components used in gasoline refining, ETBE has not been widely used in the United States refining industry in the past, giving it even more of a negative reputation among industry members. Why ETBE is acceptable in Europe and not in California is a mystery to many in the fuels industry.

During the time that Hjelmco 80/87 was produced and sold as Avgas 80 in Sweden, it was manufactured in Czechoslovakia from 1981-1985, until that facility was shut down. When that occurred, the production moved to Germany from 1985-1992 (Hjelmberg, 2004). When the production moved to Germany, the refiner’s knowledge base was far larger than that of the Czechoslovakian counterparts (Lars Hjelmberg, 15). At that time, Lars began exploring the possibilities of reformulating the 80/87 and trying to devise a higher octane fuel for the Sweden avgas market.

In the spring of 1991, Hjelmco introduced Hjelmco 91/96 (Hjelmberg, 2004). The 91/96 fuel had a motor octane number (MON) of greater than 93, and a research octane number (RON) of greater than 98. This fuel, however, did not comply with ASTM D910 Table 1, as did the grade 80, because there was no additional note in the higher octane specification authorizing the removal of TEL from the final fuel, as was noted in the 80/87 specification. Basically to meet the D910 spec for any fuel other than grade 80/87, the fuel was required to have TEL. If there was not TEL, the fuel was not compliant with the specification, regardless of whether the fuel performed properly or not.

Despite the fuel not meeting D910 due to the issue of TEL inclusion being required under D910, Hjelmco released the product for distribution in Sweden in 1993 (Hjelmberg, 2004). Since the fuel did not meet the ASTM D910 standard, to which all aviation fuels were certified, distribution was much more complicated. Hjelmco products were still largely unavailable outside of Sweden, as they were not governed by a specification.
There were several attempts to remove the requirement for the inclusion of TEL from the D910 fuel grades. Hjelmco’s ASTM delegates were largely unsuccessful in this endeavor as the Subcommittee that governs D910 was very protective of altering a time-proven specification. For many years, animosity existed between these two groups stemming from the several heated battles that took place over this issue. The problem was that this area was where science, politics, decades of individual personal experience fuels experts, and no small amount of individual personally all crossed paths at the same place. Had the Hjelmco fuel been introduced into the ASTM process two decades later, it might have received a warmer reception. But at the time it was introduced, the expertise in fuel was based on a firm understanding of hydrocarbon fuels and TEL performance, and so the ASTM committees were hesitant to launch into unknown directions with untried chemicals. In the defense of the ASTM committee members, it should be said that their very conservative attitude on this issue, was founded in no small part to the need to have a universal drop in fuel and a fuel that they knew was guaranteed to be as safe as the 100LL it was replacing.

Despite the ASTM’s resistance to change D910 to eliminate the call out for TEL, Hjelmco used its corporate-owned Piper Arrow aircraft to prove that the fuel worked in all regimes of flight. In 1995, Lycoming Engines helped accelerate the acceptance of Hjelmco 91/96 by examining Hjelmco Oil’s data on Lycoming engines for inclusion on Lycomings list of approved fuels. In 1995, Lycoming Service Instruction 1070L was released to supersede the previous versions, service instruction 1070L included unleaded 91/96 on their list of approved fuels. The service instruction states that 91/96UL is approved for use in certain Lycoming Engines and is the “trade name for colorless unleaded fuel produced by Hjelmco Oil, Inc. of Sollentuna, Sweden and stated by the company to conform to ASTM D910 specifications except for the lead content and colorant. Specification of Hjelmco AVCAS 91/96UL (or any other brand/trade name) does not constitute a commercial endorsement by Lycoming” (Lycoming Engines, 2010). Since Piper Aircraft Company references the engine manufacturers service instruction
for list of approved fuels, this addition by Lycoming allowed Hjelmco 91/96 to immediately be certified for use in their aircraft that used Lycoming engines. Hjelmco began selling 91/96 all throughout Sweden and over 60 airports and used by over 700 aircraft (Hjelmberg, 2004). According to the company’s website, the Hjelmco 91/96 was originally produced in Finland from 1991 until 1998, after which the production was moved to Sweden.

Since the fuel was produced and used it primarily in Sweden, neither the FAA nor the ASTM had jurisdiction over its use or certification. The certification aspect of the fuel was accomplished via the OEM authorizing the use of the fuel on their equipment; whereas, the regulation fell to the Swedish Civil Aviation Authority (CAA). The CAA commented on the operational use of Hjelmco 91/96 at an alternative aviation gasoline seminar in Brussels back in 2004, which was sponsored by the FAA. The CAA focused on the effects of changing from a low-lead fuel to an unleaded avgas. They concluded that the biggest area of concern was exhaust valves if “transition was not performed in a controlled way” (Swedish Civil Aviation Authority, 2004). By “transition..in a controlled way” the CAA meant that older aircraft engines which needed lead for valve cooling and valve lubrication would have to receive modern engine valves prior to the aircraft being able to use the unleaded fuel. The CAA also noted that the performance of an aircraft engine degraded in a controlled way, slowly over time, if a failure was going to happen which was to be attributed to the use of unleaded aviation fuel. They were also quick to point out that to date, “no improbable condition has been recorded thus far” (Swedish Civil Aviation Authority, 2004).

Some other areas of interest that were addressed by the CAA during their presentation included things such as previously dormant failures becoming visible after switching to an unleaded Hjelmco 91/96. What they were referring to was a failure of a part or engine system that might occur after switch to 91/96. An example that was used was that a pilot would not be able to set the fuel mixture
properly. In this example, a pilot previously running on 100LL with a single piece main venturi on the engine would experience a dangerously weak fuel mixture when using Hjelmco 91/96. Previously, if the pilot had been using a 100 octane fuel, there might have been enough additional motor octane number points in the fuel to overcome as situation where the pilot set the mixture too lean, with the pilot none the wiser. When using an unleaded Hjelmco 91/96, this lean mixture problem might actually become worse and the pilot would notice a problem with engine performance during operation of the engine.

Other potential problems to switching over to Hjelmco 91/96UL consisted of things such as a lower fuel level in the carburetor, and a deficiency in heat transfer between valve guide and cylinder head, primarily due to the absence of TEL. The CAA also commented that another possible lurking failure was the fact that “engine manufactures do not want to recommend designated oils or additives for use together with UL avgas” (Swedish Civil Aviation Authority, 2004). However, Hjelmco Oil was quick to point out that this was already been done by Lycoming Engines as its own 91/96 is approved, but was the only UL fuel to be approved. One final factor that the CAA called attention to regarding the use of unleaded fuels such as Hjelmco 91/96 was that fuel systems may give incorrect fuel level readings, which can be attributed to the slightly lower density of Hjelmco 91/96.

To refute these points and prove that Hjelmco 91/96 was a viable alternative to 100LL, in 1999 the company published that Hjelmco 91/96 has been successfully used for more than eight years, and has incurred less than 10 technical events, and 7 engine events in 384,000 flight hours. This provided an overall reliability of $1.82 \times 10^5$ (Hjelmberg, 2004). Hjelmco Oil claimed that 91/96 has created “fewer problems than 100LL did when it was introduced in the 1970s” (Hjelmberg, 2004).

Today Hjelmco recommends the use of this fuel if the minimum certified fuel grade, from the engine manufacturer, is 91/96 or lower. The company also recommends the use of their fuel only if the engine as installed has: proper cooling, engine oil recommended for operation with UL fuel, & and oil
additive is used. If all of these parameters are met Hjelmco guarantees safe operation on 91/96 (Hjelmco Oil AB, 2011). Aside from Hjelmco’s other suggestions, in general they recommend that “all aircraft engines up to 180 horsepower and between 230-260 horsepower, are suitable for Hjelmco 91/96 UL fuel” (Hjelmberg, 2004).

As far as a total replacement for 100LL, Hjelmco 91/96 has had few trials to test its merits. However, in March 2002 the company used a new-style ignition system (PRISM) made by General Aviation Modifications Incorporated (GAMI) with their Hjelmco Avgas 91/96. A Piper Chieftain with turbocharged Lycoming 540 engines ran on Hjelmco 91/96. It was reported that at rated horsepower (350), with all the CHT’s at red line (500° F), the engines were “free of harmful detonation or pre-ignition” (Hjelmberg, 2004). Hjelmco claimed that this was a major milestone in the replacement for 100LL; essentially claiming that Hjelmco 91/96 could indeed replace all of the need for 100LL. While this may be true, Hjelmco 91/96 would not be a direct replacement for 100LL as all of the engines that required a 100 octane fuel would have to be retrofitted with an entirely new ignition system. This would not only be costly to pilots and aircraft owners but also to engine and airframe manufacturers that would have to recertify their existing equipment. This would not only be cost prohibitive, but logistically nearly impossible, thus the manufactures have been unwilling to make this change.

Recently the EASA, the European counterpart of the FAA, released Safety Information Bulletin (SIB) 2010-31 regarding the use of Hjelmco 91/96UL in aircraft. This SIB states that “Hjelmco 91/96UL [...] meets the requirements of ASTM D910 for grade 91/96 (except colour) [...] and may be used, if approved for the particular engine types. No additional approval is required for the aeroplane, provided the aeroplane is already approved for operation with avgas (according to ASTM D910)” (EASA, 2010). This essentially it allows for the use of Hjelmco 91/96 UL in all airplanes that are approved for a sub-100 octane fuel when flying in Europe. The FAA has not yet taken such a stance. For the time being this
further legitimizes the flights being conducted on low-compression engines running Hjelmco 91/96UL in Europe. Though this fuel does not address the issue of replacing 100LL altogether. Hjelmco has paved the way for unleaded fuels to replace a leaded fuel industry. Due to the lack of +100 MON UL fuels provided by Hjelmco, an all out replacement of 100LL is impossible. Nonetheless, Hjelmco serves to demonstrate that an unleaded alternative to 100LL may well come from a small businesses, rather than from a traditional large oil companies.

In recent years persons from Hjelmco Oil have been active players in the ASTM process, though with no intentions of certifying their own fuel through ASTM. Hjelmco does not indicate that it intends to make a + 100 MON unleaded aviation gasoline. However as the activity at ASTM has progress to find ways to develop fuels beyond the D-910 specifications, to include new unleaded fuels, bio-based fuels, and synthetic fuels, Lars Hjelmberg has been a valuable resource to the ASTM committees developing these new specifications.

Hjelmco today has established a distribution network at over 60 airports throughout Sweden, and delivers 100LL avgas, Hjelmco 91/96UL, and Jet A-1 to these locations. Hjelmco also distributes its 91/96UL to one Airport in Japan (Hjelmco Oil AB, 2011). This is the only current distribution network that this fuel is available through.
Chapter # 5
Automobile Fuel for Airplanes

Nearly all in the fuels industry recognize that the era of leaded aviation gasoline is coming to an end. Some in aviation have turned to what they believe is the simplest answer: automobile gasoline. Those who have been pilots for quite some time may not even realize this option exists. However, research surrounding the use of automobile gasoline, known as mogas in the aviation industry, started almost a decade before the introduction of 100LL to the aviation market. With the daily use of mogas of 380,000,000 gallons/day in the United States for automotive purposes, which is more than the total amount of 100LL used in one year, mogas at first blush might seem like a reasonable alternative or replacement for 100LL. In this chapter we examine the history of the work that has gone into mogas for use in aviation, technical hurdles that prevent mogas from being used as a replacement for 100 LL, the certification and specification for use by both FAA and the ASTM, where mogas as an aviation gasoline stands today, and its potential to replace 100LL.

Nearly a decade before 100LL was introduced to the market, the Experimental Aircraft Association (EAA) “began testing and evaluating alternate fuels for aircraft piston engines in 1964. These included not only automobile gasoline, but also ethanol” (EAA, 2010). This effort received much more attention during the “Arab Oil Embargo of 1973”, in an attempt to streamline the avgas supply chain into the automobile fuel supply chain, as to not isolate aviation fuel as a further boutique fuel.

This has always been, and remains the main goal, of those who have attempted to use mogas for aviation. The crux of the argument lies within this point alone. It is not based on an improved or equal performance as compared to 100LL.
The EAA has principally led the charge from the beginning in moving to allow mogas for use in aviation. The testing began in the early 1970’s, the EAA commissioned an Experimental Cessna 150 that had multiple monitoring instruments onboard for collecting in-flight data on experimental fuels such as mogas. The Cessna 150H, registration number N23107, was tasked and partially funded by Amoco Oil to research mogas on the Continental O-200 engine (EAA Museum, 2009). EAA began conducting flights to gather data to prove that mogas could be used in general aviation aircraft. While “the Cessna 150 is the fourth most produced civilian plane ever, with 23,839 aircraft produced” (Thompson, 1991); the testing may have been slightly academic since this aircraft and engine only required an 80 octane fuel to begin with. The O-200 was originally certified from Continental on Grade 80/87 (red) leaded aviation gasoline. Continental also pointed out that 100LL should only be used as an alternate fuel for the O-200 engine when Grade 80/87 was not available (Continental Aircraft Engines, 1977). While the underlying intentions were of the testing of the Cessna 150 were good, the results gathered under this testing program were positive, the results were only valid to prove that mogas was a sufficient replacement for Grade 80 leaded avgas, not 100LL.

Note that when referring to the most current copy of ASTM D910, 80/87 is referred to as Grade 80 avgas in Table 1. It specifies that the MON of this fuel should be a minimum of 80 MON (ASTM International, 2007).

During the early 1980s’ EAA worked to share flight data from the Cessna 150 flights with the FAA to prove that mogas was an acceptable fuel in certain type of aviation engines. In 1982, “EAA received approval from the FAA to provide an STC (supplemental type certificate) that allowed certain types of aircraft engines to use auto fuel instead of more costly avgas” (EAA, 2010). As a show of support for the program, the first pilot to legally fly in an aircraft with automobile gasoline as the primary fuel powering the aircraft was, then FAA Administrator, Lynn Helms (EAA, 2009). Following initial certification of the
STC in 1982, Grade 80 avgas (red) became scarcer as the industry began to move to a single fuel supply of 100LL. With Grade 80 avgas disappearing rapidly at airports, several questions and concerns arose from the FAA on the acceptability of using mogas as a replacement for 100LL, since it was meant to only replace Grade 80 avgas.

In response to several public comments made by the FAA, the EAA wrote the FAA for clarification on the use of mogas under the STC. The Small Airplane Directorate of the FAA clarified their statements in a letter to the EAA in 1998 by saying, “Autogas use has been extensively compared, tested, and analyzed. Autogas has been shown to be an acceptable alternative to avgas for the airplanes and engines approved for such use.” They went on to say that, “Airplanes and engines approved for autogas use have met the FAA certification requirements for engine detonation, engine cooling, fuel flow, hot fuel testing, fuel system compatibility, vapor lock, and performance” (FAA - Small Airplane Directorate, 1998).

Under the STC, as issued, the fuel must comply with ASTM D4814 the Standard Specification for Automotive Spark-Ignition Engine Fuel. Though ASTM D4814 is a lengthily specification designed for automotive fuel, there are very few parameters that all fuel batches produced in the United States must uniformly meet. This means that fuel constancy throughout the United States is, for all practical purposes, nonexistent. For automotive engines these variations in gasoline have been partially compensated for by advance electronic controls, and advanced engine designs. In some cases automotive engines do not run well at all on certain batches of fuel produced under this specification. In short, automotive fuel produced under this specification has great variations and in fact does not always perform well, or even acceptably. This variation in production standards is because ASTM D4814 was published with the idea that the specification served to establish “requirements of automotive fuels for ground vehicles equipped with spark-ignition engines” (ASTM International, 2009). The original
subcommittee assumed that the specification was just limited to ground based vehicles. All of the safety and reliability checks that exist in aviation gasoline to ensure its safety through all regimes of flight are nonexistent in the D4814. Basically if automotive gasoline does not perform well, the user burns more fuel per mile, can haul a little less payload, may have to accelerate slower, or may have to occasionally pull over and get better fuel, but if aviation fuel is not good, these variations can be catastrophic.

However, that does not mean that originally, mogas was unsafe for aviation use. The STC was meant to show that the use of the mogas fuel would not yield an unsafe condition of flight. By a close examination of D4814, one notices that the specification is very different from the D910 in that the specification looks more like a smorgasbord of options and climates and locations within the US; whereas, D910 is constant worldwide. That is to say that automotive gasoline is made differently in different parts of the United States, based on the geographic differences around the country, whereas aviation gasoline is designed to be the same no matter where it is produced and used in the world. ASTM D4814 denotes “various characteristics of automotive fuels for use over a wide range of operating conditions. It provides for a variation of the volatility and water tolerance of automotive fuel in accordance with seasonal climatic changes at the locality [in the US] where the fuel is used” (ASTM International, 2009). The specification is mainly comprised of various explanations and background information of why limits were set the way they were. ASTM D4814 has twelve small tables which layout the requirements the fuel must comply with. Table 1 discusses the vapor pressure and distillation information and correlates each set of fuel choices labeled AA – E with a certain set of parameters.

Table 2 of D4814 details the only stable part of the specification that remains constant despite the location or time of year. Included in this table are the lead content, corrosion levels, sulfur, and oxidation levels. While these parameters remain fixed, they do not fix the important parts of fuel that on which pilots rely, such as MON, RVP, or distillation curve. While the parameters listed in Table 2 are
similar to what we find in D910, the spec ignores the overlying problems that surround the parameters in D910 aviation gasoline, and are not enough on which to base an aviation approval. In Table 3, vapor lock protection temperatures are specified for one of six classes of fuel blends, labeled 1-6. The classes of fuel specified in Table 3 are combined with the classifications given in Table 1 and are referenced in Table 4. While this may seem confusing at first, it is quite simple, when viewed graphically in Table 4 below.

Table 4, which is the heart of the ASTM D4181, is shown below in Figure 1. The table has listed on it all of the states within the United States along its left side. Some states are just listed once; whereas, others like California are subdivided into several sectors due to geographic variations and demographic variations. Along the top side of Table 4, each month is listed. This means that each state in the United States have a different fuel specified for each individual month. While it is true that some combinations are repeated throughout the year and location, a singular product cannot be guaranteed throughout the country. Essentially, this means that there exist 36 different combinations of mogas for use in the United States.
Despite the wild variations and multiple combinations, EAA was able to prove to the FAA that this was not an operational or safety issue. Data that the EAA generated from their Cessna 150 flights
proved that various mogas blends were sufficient to provide adequate safety and reliability for operation in their engine. This was not a surprising conclusion. Remember that many early low performance engines in aviation ran on automotive gas, and poor automotive gas at that. In addition the aircraft advocated by the EAA for being eligible for using mogas were low compression engines, operated at moderate temperatures, and low altitude.

During the 1980’s and 1990’s this was indeed the case and mogas for low-octane engines could be found at multiple airports throughout the United States. The airports that carried this fuel put in separate tanks that were outside of the auspices of the established aviation fuel distributors. One such airport that offered mogas in a separate, on-airport, tank was Delphi Municipal Airport in Delphi, Indiana (119). In fact, Delphi Airport management wanted to be one of the early adopters of the new fuel and put in a tank in early 1985. Delphi Municipal Airport was the third airport in the United States to offer mogas for use in aircraft (Stirm, 2010). Placing a tank at the airport allowed pilots to fill their aircraft as they normally would with 100LL. Without an on-airport tank, pilots would be relegated to using portable fuel cans to transport fuel to and from the local gas stations. This introduced a whole new set of problems that would not have otherwise existed. The main concern is that pilots would be using fuel cans that were dirty and further introduced contamination into their aircraft’s fuel system. A second major concern of off-airport fueling was in the quantities required to fill a general aviation airplane. In the case of the Cessna 150, for example, a pilot would need to transport 30 gallons of fuel from the automotive gas station to the airport. Assuming the pilot used 5 gallon cans to transport the fuel, the pilot would need to cart 6 cans from the gas station to the airport. While this may not be a lot, it is probably the least overall quantity transported, as the Cessna 150 was one of the smallest of those STC’ed for mogas. The quantity doubles when a slightly larger Piper Cherokee is examined. The on airport tank at the Delphi Municipal and other airports with mogas fuel tanks saved pilots from having to self-transport and ensured that the fuel, usually delivered from the local agricultural farm co-op, was of
constant high quality. Over the years this model of supplying mogas at small airports has caught on. In fact by 2011 there were more than 100 airports in the continental US offering mogas at the airport (Chouby).

To facilitate the use of mogas, aircraft had to be approved on an individual basis to be able to use the fuel. This approval involved a design change process known as the Supplemental Type Certificate (STC) process. This process was a regulatory method controlled by the FAA to allow US based aircraft to have their original manufacturers’ designs altered to accommodate some design change. In this case the design change was to accommodate the use of mogas in an aircraft certified for aviation gasoline. For some aircraft models the design approval called for little more than the addition of a line in the pilot handbook allowing and a label on the fuel filler cap calling out the approval of the mogas. For other models of aircraft the requirements to satisfy the FAA of safe flight on mogas required more extensive changes. In general, however, the FAA would only approve these changes for an STC for aircraft known to be able to run acceptably on mogas. Throughout the years since the mogas projects started for aircraft, groups like EAA and Petersen Aviation, Inc. began securing various STC’s for multiple aircraft/engine combinations and reselling them to aircraft owners. Over the years many aircraft were modified to mogas, and the aircraft performed acceptably. So for one class of aircraft there did seem to be an unleaded fuel solution.

The only problem with this system was that since the STC, allowing the use of mogas, was issued in 1982, the fuel had to conform to D4814 as it was written at the time the fuel was certified by the FAA. ASTM bylaws regulate that specifications must be balloted on and renewed once every five years. While this holds true for all specifications, this has not affected aviation negatively since the specification for 100LL has essentially remain unchanged since 1972. With autofuel however, this is not the case. In the past two decades, the nation has began to adopt the blending of ethanol with motor fuels for several
different reasons, including: reducing our dependence on foreign oil, increasing our ability to use domestic bio-fuels, the use of ethanol as an oxygenate for cleaner tailpipe emissions, an increase parameters such as motor octane without having to add high-grade petroleum derived alkylates into the autofuel blend-stock. These petroleum derived alkylates were what replaced the lead in automotive gasoline. Alkylates were a type of hydrocarbon molecule that come from what was known as an alkyl group. Without getting too in depth into chemistry, suffice it to say that these were a particular combination of carbon and hydrogen atoms arranged in a particular way. Because of their particular groupings, they tended to prevent gasoline from spontaneously combusting, or detonating, in an engine cylinder. For decades petroleum chemists worked to try to make alkylates work in aircraft applications, but without success. Of the many organic chemicals evaluated each of them suffered from one or another serious flaws, whether they were corrosive, toxic, had low vapor pressure, high vapor pressure, etc. Unfortunately, alkylates were not a suitable replacement for TEL in many types of engines, including aircraft engines, however, for automotive use where cylinder diameters were relatively small, chamber pressures were relatively low, and spark ignition timing was actively varied, the alkylates performed reasonably well.

A common misconception is that individual States and even the Federal Government have required current motorfuel to have ethanol be blended into it. In the past, “The Clean Air Act of 1990 mandated reformulated gasoline (RFG) contain additives such as MTBE or ethanol to meet EPA fuel oxygenate standards; [however] The Energy Policy Act of 2005 eliminated the mandatory oxygenate requirement from RFG” (EAA, 2008). But while the use of oxygenate additive is no longer a requirement in 2011, ethanol is still blended into the fuel for many of the other reasons listed above. While States may not “require” producers to use ethanol, in some corn growing states it is strongly encouraged. As the price of crude oil continues to rise past $100 per barrel, producers continue to look for an anti-detonation compound that is not derived from expensive crude oil. For automotive use, ethanol has
proven to be a good substitute. While ethanol has less heat than the alkyates that it replaces, and the fuel does not perform as well, modern automotive engines have a complex array of sensors, active engine controls, and other computerized engine management systems, which allow the engines to run on very poor fuel. In fact, the typical automotive users might only notice the fact that the car is burning a little more fuel than usual when ethanol is substituted for alkylates. Unless the automotive user is demanding full power from the engine routinely and continuously, they might not really notice the difference.

The problem now becomes, with using mogas, is that the way the STC was originally issued, it did not allow for any amount of ethanol to be in the final fuel used for flight. This has become a big problem as most all motor fuel in the United States today contain anywhere from 7-15% ethanol blended in with most grades of automobile fuel. While signs on the gas pumps at the filling stations may say that the autogas contains no more than 10% ethanol, it is not unusual to find samples taken from automobiles with substantially more than 10% ethanol in the fuel.

In the past few years nothing has caused more of a problem or confusion with STC holders and issuers alike. During the initial stages of ethanol being blended into mogas, some STC holders chose to ignore the undercurrent that was beginning to stir surrounding the use of ethanol, in fear that it would invalidate their STC. Multiple differing opinions were alive and well and leaving pilots confused. In order to clarify their position, in October of 2006, the FAA issued a document attempting to explain the use of ethanol blended motorfuel in aircraft with mogas STC’s. In a Special Airworthiness Information Bulletin (SIAB) the FAA called attention to an “airworthiness concern where you could have alcohol (ethanol or methanol) present in the automobile gasoline on any General Aviation airplane” (FAA, 2006). The SIAB stated that, “Automobile gasoline containing alcohol is not allowed to be used in aircraft” (FAA, 2006). There were a couple of reasons listed on why autofuel containing ethanol was prohibited for use in
aircraft. First and foremost the FAA called to attention that the overall volatility of the fuel was altered when ethanol was added to it. This could lead to vapor lock issues when trying to start an aircraft engine. Aviation gasoline had a very tight range for volatility (i.e. vapor pressure) if the vapor pressure were outside of the standard band of 5.5psi to 7.1psi (ASTM International, 2007), the fuel might not be volatile enough to start an engine in extremely cold or extremely hot conditions. Another point addressed by the SIAB was when using autofuel that may have ethanol blended was the corrosive nature of ethanol. The FAA explains that aircraft fuel system components were not made to withstand the corrosive nature of the added ethanol. Also, since some aircraft had been flying for over 40 or 50 years, the natural rubber components that were designed for robust, ethanol free, hydrocarbon-based fuels were unable to withstand the abrasive action the ethanol imparts on them. These problems lead to reduced fuel system performance and eventually failure.

Another issue that reported by the FAA was the tendency for phase separation in ethanol blended mogas. This issue was not as prevalent when mogas was used for automobiles; however, when used in aircraft, fuel was affected by rapid (more than automobiles) changes in altitude. When the aircraft climbed, the fuel was rapidly cooled as the temperature aloft fell. This rapid change in temperature triggered what was known as phase separation, which was where the oxygenated ethanol separated from the hydrocarbon based gasoline. The issue was that, “when the alcohol separates from the gasoline, it may carry water that has been held in solution and that cannot be handled by the sediment bowl” (FAA, 2006). When this phase separation occurred, it could lead to the water freezing in the fuel lines, causing fuel starvation, or a slug of water could pass into the engine at just a point in time when engine power was needed, causing the engine to stop running. Or if the alcohol separated from the water, the gasoline would no longer have had any anti-knock, or anti-detonation, protection. This would then have lead to severe engine knocking, resulting in the potential for a catastrophic engine failure in flight.
Quite possibly one of the largest effects of ethanol blended mogas was that when ethanol was used, it decreased the overall energy content in each gallon of the fuel. The SIAB pointed out that “Methanol has approximately 55 percent of the energy content of gasoline, and ethanol has approximately 73 percent of the energy content of automobile gasoline.” The FAA went on to state that the “greater the amount of alcohol in the automobile gasoline, the greater the reduction in the aircraft’s range” (FAA, 2006). For an automobile a decrease in range was generally, only an annoyance of more frequent stops at gas stations. For an aircraft a decrease in range could have been the difference between making it to the destination and crashing somewhere away from an airport. The biggest problem was that pilots could not compensate for this shortened range, because they never would have any idea what type of fuel they had on board. Again, unlike automobiles where people routinely filled up the gas tank at a fuel stop, it was routinely necessary for aircraft to carry only the required amount of fuel for the distance needed, plus a safety reserve. Often aircraft could not carry full tanks of fuel due to the inability to carry the extra weight of the fuel, when fully loaded with cargo and passengers.

On top of all of this, the lower heat content of the alcohol fuel could have resulted in lower engine power, which could have resulted in an inability of the aircraft to climb as the performance charts for the aircraft indicated. If the aircraft were not able to climb properly, the aircraft might not have been able to clear obstacles at the end of the runway, or climb over mountains or adverse weather. All of these issues were individually extremely hazardous to safe aircraft operation and likely fatal for flight crews and passengers.

There were few remedies mentioned by the various agencies involved in mogas STC’s, such as FAA and EAA. The EAA took a stance of urging pilots to protest potential legislation that would have required mandatory amounts of ethanol to be blended with mogas. The FAA provided recommendation to pilots in the SAIB previously mentioned. The FAA, like the EAA, first and foremost urged pilots only to
use mogas that was compliant with the ASTM specification that the STC was issued under. This was becoming nearly impossible as most local gas stations did not offer an ethanol free motorfuel. In most cases, ethanol free fuels were nearly impossible to identify as they were rarely labeled as “ethanol-free.” The FAA provided some direction to those pilots that were unsure if fuel contained ethanol or not. They recommended that pilots use a container marked with ten equally-spaced demarcations; then, “add one part water into the container and then add nine parts of automobile gasoline. Shake thoroughly, let stand for 10 minutes or until automobile gasoline was again bright and clear. Record the apparent level of the line between the automobile gasoline and water” (FAA, 2006). In theory, adding the water to the alcohol laced gasoline, would cause the alcohol to leave the gasoline and combine with the water. After the ten minute wait, the amount of “water” appearing in the graduated tube should appear to be more than was originally put in the tube. EAA sold a similar device for this exact purpose; it was called an auto fuel Alcohol Test Kit, and it allowed pilots to quickly perform the test mentioned in the FAA’s SIAB. (EAA, 2009). If the pilot did find that the fuel in question contained ethanol due to the rudimentary field test, the FAA advised that this fuel was “not allowed to be used in aircraft” (FAA, 2006).

As of 2011, there were less than 2500 gas stations in the continental US offering ethanol free gasoline (Pure-gas.org, 2011), out of a total number of 118,756 gas stations (US Census Bureau, 2007). This meant for pilots with mogas STC’s, only 2% of gas stations offer a legal fuel to power their airplane. Of those that already paid to convert their airplane, and who could not find ethanol free gasoline, the only remaining legal option was to go back to using 100LL.

For those pilots who chose to continue to fly on alcohol containing mogas, there remains risk beyond those of safety of flight. Every insurance company, requires that an insured aircraft be airworthy and in compliance with Federal regulations if the aircraft is to be insured. If the aircraft is not
flown in compliance with regulations, or if the aircraft is maintained and operated according to accepted methods, the insurance companies often do not pay if there is an accident. An aircraft owner or pilot can suddenly find themselves with no insurance if there is an accident and the aircraft has alcohol in the fuel tanks. While some aircraft owners might choose to accept the risk of the loss of their aircraft, the owners do not realize that they also lose any protection against damages to other people or property. In the mythical example of an aircraft that crashes into a children’s hospital, lawyers will line up around the block to sue the aircraft owner, and the insurance company will be nowhere in sight. In fact, the alcohol test kits, described above, are a standard tool in the tool kit for an aircraft insurance adjuster, and is one of the first things tested for by the insurance company for any accident claim.

Though the future cannot be accurately predicted, the possibility that ethanol is going to be blended into mogas in the future is very unlikely. In fact, politically driven state policies are moving to enact increasing the amount of ethanol in motorfuels. The following excerpt shows the future of ethanol blended motorfuels, “The Environmental Protection Agency today agreed to let refiners add as much as 15 percent ethanol to a new blend, up from the current 10 percent” (Parker & Chapman, 2010). With daily revelations on this front, the end of ethanol blended motorfuel in the US is not likely, barring any rapid change in political direction. This is not good news for those who rely on this ethanol free mogas to power their airplanes. Since ethanol is blended in at the refinery level of the supply chain, it is nearly impossible to obtain specialty loads of unblended mogas for aviation use. Under these circumstances, mogas is very much unfit for use in aviation, under the auspices of an STC or as a replacement for 100LL. Beyond the ethanol, most mogas is blended to have less than 90 MON. This fact alone makes it insufficient for use as a replacement for 100LL, despite the ethanol content. Even if one were able to obtain a specialty load of pre-bled (ethanol free) mogas, refiners usually only have an 83 AKI (AKI=RON+MON/2) product available. A sub-80MON product would not provide the necessary anti-knock margin required by +100MON aviation engines. Despite the attractiveness of using the world’s
most supplied petroleum fuel for use in aviation, for all of these abovementioned reasons, mogas is not sufficient for use as a replacement or alternative for 100LL.
Chapter 6

82UL Aviation Gasoline

The idea of the disappearance of 100LL is not a new one. In fact, most pilots say that they have heard of this notion for at least the past 20 years. The industry players have also been discussing this possibility seriously for at least the past four decades.

In 1988, in Baltimore, the industry held a Future Fuels for General Aviation Symposium to discuss the short and mid-term future of general aviation beyond 100LL (ASTM Subcommittee D02.J, 1998). The conclusion was that general aviation would continue to heavily dependent on the availability of high octane aviation gasolines. It was understood that the only method by which booting the octane had been occurring was through the addition of tetra-ethyl lead (TEL). With the threat of the disappearance of TEL, the industry members concluded that, “the long term survival of the piston fleet will be based on the ability of the general aviation industry to adapt its products to use fuels available in large pools” (ASTM Subcommittee D02.J, 1998). It was decided at the symposium that a sort-of emergency fuel be specified for use to continue to allow general aviation to function, beyond TEL. Based on the conclusions from the symposium it was recommended that there be a, “drafting of the new Grade 82UL Aviation Gasoline Specification was initiated during ASTM Committee D02 Meeting held in New Orleans on 12 December 1989” (ASTM Subcommittee D02.J, 1998). Work on 82UL has progressed with the purpose of finding an unleaded aviation gasoline that can fuel the largest number of aircraft possible. After a review by the petroleum producers of all of the possible additives to replace TEL it was determined that 82 octane was the best that could be produced. After a review of all existing aircraft and engine specifications, it was determined that 82UL would fuel a majority of the general aviation aircraft, the exact number of which remained in debate.
The task force for 82UL began testing by having sixteen different test fuels prepared for testing. There were twelve different candidate 82UL fuels blended and four reference fuels consisting of both 100LL and mogas samples. Each one of the twelve candidate blends of 82UL exhibited varying performance characteristics to establish the blending envelope for the 82UL specification. 82UL gasoline was essentially an unleaded aviation gasoline base stock, similar to what TEL was added to in order to derive 100LL. Added to this base stock was “specific aliphatic ethers, synthetic hydrocarbons, or aromatic hydrocarbons” (ASTM International, 2004); or in other words, methyl tertiarybutyl ether (a.k.a. MTBE). MTBE was classified as an oxygenate since it raised the oxygen content of gasoline. MTBE had been used in U.S. gasoline at low levels since 1979 to replace TEL as an octane enhancer (U.S. Environmental Protection Agency, 2008). It was then natural that this task force undertook the use of MTBE as a natural replacement for TEL to solve the aviation gasoline problem. The specification for 82UL limited the ether content to 2.7% by mass, in the finished fuel (ASTM International, 2004). At the time of this research, the use of MTBE in fuels was on the rise, according to the EPA, “Since 1992, MTBE has been used at higher concentrations in some gasoline to fulfill the oxygenate requirements set by Congress in the 1990 Clean Air Act Amendments” (U.S. Environmental Protection Agency, 2008). However, MTBE was proving not to be the magic bullet that some were hoping for. EPA cited that, “MTBE dissolves easily in water and does not ‘cling’ to soil very well, it migrates faster and farther in the ground than other gasoline components, thus making it more likely to contaminate public water systems and private drinking water wells” (U.S. Environmental Protection Agency, 2009). Furthermore, the EPA stated that, “MTBE does not degrade (breakdown) easily and is difficult and costly to remove from ground water” (U.S. Environmental Protection Agency, 2009).

Though there was no national standard for MTBE pollution established, the EPA did issue a Drinking Water Advisory in 1997. The advisory was a non-regulatory document that provides Consumer Acceptability Advice and Health Effects Analysis on MTBE. The report claimed that, “there is little
likelihood that MTBE concentrations between 20 and 40 ppb in drinking water would cause negative health effects;” however, they went on to state that it was possible your water would taste and/or smell like turpentine if MTBE was present at these levels. (U.S. EPA, 2007). Proponents of banning or severely limiting MTBE as an additive pointed to a famous case of ground water contamination involving MTBE following the use of MTBE in automobile gasoline for a period of time. This incident of MTBE contamination occurred in 1996 in Santa Monica, California and was the first major incidence of MTBE contamination in the United States. The EPA recounted that, “Santa Monica learned that two of its drinking water wellfields, Charnock and Arcadia, were contaminated with MTBE at levels as high as 610 ppb and 86 ppb respectively. In response, the two wellfields, representing 50 percent of the city’s drinking water supply were shut down and the city began purchasing replacement water” (U.S. Environmental Protection Agency, 2009).

Despite the perceived negativity surrounding the use of MTBE, the task force continued to examine its use as a replacement for TEL in aviation gasoline. The research task force was lead by members of Cessna Aircraft Company. As a major general aviation manufacturer, reliant on the existence of an aviation gasoline, Cessna spearheaded the development of this specification by conducting most of the research on the fuel samples. It should however be noted that Cessna personnel did not have illusions that 82UL would be a direct replacement for 100LL. During a recent personal discussion with Cesar Gonzalez (who led the 82UL projects at Cessna), he said “we [the task force] were trying to come up with a safety net, just in case” (Gonzalez, 2010). In addition to Cessna’s participation, the Phillips Chemical Company, and the Diamond Shamrock - Three Rivers Refinery produced the various test samples of fuel. Most of the tests were conducted under the auspices of Cessna; however, the Southwest Research Institute (SwRI) carried out many of the laboratory tests on oxidation stability, gums testing, and long term storage among others. Many of the materials compatibility tests were carried out via rig tests developed by Cessna engineers. These rigs emulated various parts of the aircraft
and engine that would come into contact with the fuel. Lycoming Engines also performed some engine endurance testing at their facility on an IO-360 engine, “using exclusively Grade 82UL Test Fuel” (ASTM Subcommittee D02.J, 1998). There were several other testing laboratories who performed minor verification tests to ensure compatibility. Their results yielded the publishing of an ASTM standard Specification for Grade 82UL Aviation Gasoline.

Of the twelve different 82UL fuels blended, “nine distinct Grade 82UL Test Fuels were specifically formulated with characteristics more severe than those posted in the Specification table of requirements” (ASTM Subcommittee D02.J, 1998). The testing began with detonation testing on candidate Grade 82UL fuels. The fuels that were used for this testing were rated below 82 MON, which was the limit of the specification (ASTM Subcommittee D02.J, 1998). This was done in order to examine the “worst case” scenario of using this fuel. As expected, the anti-knock characteristics were not as good as those of the 100LL fuels. This was due to the lower MON exhibited by the Grade 82UL fuel and was expected. In fact, according to the specification, “Traditional leaded aviation gasolines have been defined by both lean and rich mixture ratings. A minimum lean mixture rating of 82.0 determined by the motor method provides satisfactory antiknock properties on engines certified for low octane fuels. Rich mixture ratings by Test Method D 909 were developed for older large displacement, high output engines for which this fuel is not suitable” (ASTM International, 2004).

With regard to materials compatibility, most of the materials were tested on rigs or test stands designed to emulate parts of the fuel system or powerplant. One of the biggest areas of concern was the engine-driven fuel pump, specifically the pump diaphragm. It was noted by both Cessna and Lycoming that the standard engine driven fuel pumps installed on the Lycoming IO-360 engines began leaking and malfunctioning anywhere after 31-90 hours of operation on Grade 82UL (ASTM Subcommittee D02.J, 1998). After the initial problems the report states that, “the original engine driven fuel pump was
replaced with a PMA approved pump which continued to operate satisfactorily for approximately 3,637 hours [...] without further problems” (ASTM Subcommittee D02.J, 1998). The term “PMA”, in this statement, simply referred to the fact that the pump was manufactured to an approved FAA specification. The overall conclusion on materials compatibility, with regard to the use of Grade 82UL, was the compilation of a list all of the materials that were considered compatible with 82UL and that could be used on the construction of new aircraft certified for the fuel. Furthermore, though it was not explicitly stated in the report, the results and conclusions lend the reader to glen that 82UL was not compatible with a majority of the materials that were found in low-octane demand aircraft, such as the Cessna 172.

Based on the research report for Grade 82UL, the task force designed a specification for an acceptable Grade 82UL Aviation Gasoline for ballot. In 1998, Specification ASTM D6227, the Standard Specification for Grade 82 Unleaded Aviation Gasoline, was approved by ASTM as a commercial specification (ASTM International, 2004). The scope of the specification clearly stated that the specification only, “covers Grade 82 unleaded aviation gasoline, which is defined by this specification as for use only in engines and associated aircraft that are specifically approved by the engine and aircraft manufacturers, and certified by the National Certifying Agencies to use this fuel” (ASTM International, 2004). The specification additionally explicitly stated that, “This fuel is not considered suitable for use in other engines and associated aircraft that are certified to use aviation gasolines meeting Specification D910 [i.e. 100LL]” (ASTM International, 2004). When compared to ASTM D910, the Table 1 of requirements for Grade 82UL varied considerably. Aside from the obvious deviation in MON from that in D910 for Grade 100LL, 82 vs. 99.5; the most obvious deviation was in the distillation curve. The distillation curve for Grade 100LL had precise minima and maxima specified; whereas, in D6227 the points that are given were much lower than those established by D910, with one of the points given as a
range rather than an exact point. The specification further explained that the reason a range was given for the 50% evaporated point was to guard against carburetor icing or vapor lock and ensure volatility.

One other major difference in the specification D6227 was that the Net Heat of Combustion was lower than that prescribed for D910 Grade 100LL. Another important parameter of operation where Grade 82UL varied from the established benchmark of D910 is vapor pressure, with the maxima being raised from that in D910 by 13kPa. No explanation for this change was reported in the D6227 specification, other than a footnote explaining that, “The vapor pressure of permissible fuel exceeding 62 kPa shall be shown on all product transfer documents, including the delivery document to the aircraft” (ASTM International, 2004). Other minor differences included the increase of the maximum sulfur content from that contained in D910 and the removal of the water reaction and electrical conductivity tests. A major addition to the properties of D6227 Grade 82UL Table 1, over D910, was the maximum alcohols and ether content levels. The specifications stated that no more than 2.7% “combined aliphatic ethers, methanol, and ethanol be added to the fuel” and that methanol and ethanol were limited to 0.3% mass. This 2.7% was where the MTBE was accounted for in the specification. When the new version of the specification was referenced, the ethers were not just limited to MTBE. The specification now allowed for, “Aliphatic ethers allowed up to the specification limit include methyl tertiary-butyl ether (MTBE), tertiary-amyl methyl ether (TAME), ethyl tertiary-butyl ether (ETBE), and diisopropyl ether (DIPE)” (ASTM International, 2004). These additional ethers were presumably acceptable substitutes following the negativity surrounding the use of MTBE in the United States. Since all three were aliphatic ethers, similar performance could be expected as compared to MTBE alone. The final requirement specified by D6227, Table 1, was that Grade 82UL be dyed purple for identification purposes. This fuel adopted the former Grade 115/145 D910 Aviation Gasoline dye tint as it was removed off of the fuel grades specified in D910.
As of today, the specification for 82UL is still a valid one. The specification was last revised and updated in 2004. However, there has not been one gallon manufactured for retail sale by the major oil refineries. The reasons are multi-fold; however, a main reason is that it is only acceptable for use by an even smaller section of the already miniscule general aviation community. This combined with the fact that there exists only a single distribution infrastructure, does not allow for easy sale to those that could use Grade 82UL. In a recent industry presentation from one of the largest aviation gasoline manufacturers in the US, he [name and company asked to be withheld] said with regard to 82UL, “quite simply it’s a lack of market demand, the market isn’t asking for it [82UL] and we are in no hurry to split apart our already deteriorating avgas market by adding another fuel […] it would be a logistical impossibility” (Name withheld, 2010).

So what then does the future hold for 82UL? 82UL is likely to continue to remain certified for use in aviation. It is also likely continue to remain as a “just in case” emergency fuel; however, at any time, if the demand exists, a small refinery might find it feasible to begin production and distribution of 82UL.

What is more important about the approval of the 82UL specification was that it provided an established path and standard by which new fuels could move through the ASTM process. For the first time in decades the ASTM had moved a radically different gasoline through the approval process. In fact, SwiftFuel, described in the next chapter builds heavily on this experience nearly a decade later to build their ASTM research report. Other candidate fuels, such as G99UL, are also likely to follow in this path to attempt certification.

From inception to publication the 82UL research report has taken seven years to compile and gain approval. This has been the proving ground for a fuel that does not fit into ASTM D910. While the fuel topic persists, even today, the requirements remains the same; any alternative to 100LL must be
able to power all aircraft designed to run on 100LL. Grade 82UL does not meet these requirements; however, it has never designed to.
Chapter 7

SwiftFuel – Sustainable, renewable, synthetic

It should be noted that this author has been a part of Swift Enterprises since 2005, and so some of the information contained in this chapter is a first person account of how Swift originated and how it became a developer of an unleaded gasoline. Some of the description provided in this chapter about the company, its founders, and the process, is given in order to show the completely different approach to the chemistry used to create a replacement unleaded aviation gasoline. This chapter also provides an extensive explanation of the process followed by Swift in moving forward in the development of a new unleaded aviation gasoline specification through ASTM. This extensive explanation is provided, not simply to chronicle the achievements of this author or others at Swift, but rather to show in detail the extensiveness of the process required to gain ASTM approval. The reader should remember that in a previous chapter regarding ASTM approval, it was noted that approval is a long process, and that collaboration with ASTM is major undertaking. In that previous chapter it has been noted that some fuel developers have chosen not to pursue the ASTM process and are frustrated by it. By reading this, the reader should gain some appreciation for the frustration expressed by these fuel developers, and the effort required to move a candidate fuel through the process.

Swift Enterprises, Ltd. was founded on January 1, 2001. The primary goal of Swift was research in the areas of power, ordnance, and propulsion. It was founded by co-owners John and Mary Rusek. John and Mary were fundamental in ordnance and propulsion from their previous eight years working at the Edwards Air Force Base Rocket Propulsion Laboratory. John and Mary came to West Lafayette, Indiana in 1998 when John was offered a position at Purdue University in the College of Aeronautical and Astronautical Engineering as an Assistant Professor. Soon after arriving at Purdue, John realized that the research he was interested in pursuing was best suited outside of the university setting. This idea
was further fostered after John met with former Purdue President Steven Beering, who encouraged John to pursue research at the rapidly growing Purdue Research Park in West Lafayette.

On January 1, 2001, following the award of a Department of Defense grant, Swift Enterprises, Ltd. was founded. The initial research of Swift focused on ordnance research and novel power generation methods. Swift’s initial task was not to make explosives; rather, it was tasked by the Department of Defense to examine how to use inert materials to intensify an explosion. These were appropriately classified as intensifiers. These materials were inert and not harmful when in a dormant state and were made to be carried by soldiers in side pouches or backpacks. When combined with traditional explosives, such as PBX, the intensifiers could increase the blast effect by up to ten times with only a third of the explosive material. The other main technology that Swift was researching in its early days was a liquid-liquid proton exchange fuel cell for power generation. This fuel cell technology was far different than any other fuel cells in that the catalyst layers within the fuel cell were flexible and non-noble metal, such as platinum or gold. These fuel cells could be run at ambient temperature and pressure and designed to produce up to 10kW of power, or more than enough to power a single family home. Combined, these technologies represented Swift’s research from 2001 to early 2005.

Swift’s co-founder John Rusek, was also a private rated pilot, and in 2005 began pursuing his instrument flight rating.

In 2005 this author was asked to co-pilot a flight to Cleveland, Ohio to drop off Swift’s President. John Rusek was to be the other pilot on the return trip. As our conversation developed back and forth, I told John that what I wanted to pursue was the development of a new fuel to replace 100LL aviation gasoline. I had gathered through independent study that 100LL might be in danger of going away in the future without a replacement fuel on the horizon to take its place. Without a fuel for the future, if 100LL did go away, future generations might not have the same freedom to fly. After a lot of pontification and
discussion, John and I returned to Purdue University Airport with a burning interest in pursuing this effort. As we pushed N735XH back into the hangar, John simply said, “Let’s do it!” which began the SwiftFuel research.

The next day, John and I began searching through the entire university library catalog and locating all the books and articles covering fuels research and findings. As we were searching through the information, we had one goal, identify what could be used to make a fuel over 100 MON that was suitable for aviation. In among the many books we looked through, we came across a book published by the American Society for Testing and Materials which identified the Knocking Characteristics of Pure Hydrocarbons. Even though the book was published in 1958, it was clear that this was the Holy Grail for aviation gasoline development. This book listed several hundred pure hydrocarbons that had been run under an ASTM test program and listed their motor-octane numbers as well as supercharge ratings. This became our guide for fuel blending and set forth a path of diligent research and study.

The approach taken by Swift was fundamentally different than the previous approaches to developing an unleaded fuel. Whereas previous efforts were aimed at finding a way to replace TEL and to solve the problem of fixing gasoline’s detonation problem, the Swift approach was to go back and define what the fuel was supposed to do in the engine. The review of the variously blended hydrocarbons provided a systematic map of what the characteristics of the liquid fuel needed to be. Once these characteristics were understood, it simply became a matter of custom designing a blend of custom made hydrocarbon molecules to perform the same way as gasoline. There was nothing magical about gasoline as the fuel for piston engines. There were a variety of hydrocarbons that could have been chosen in the early days of piston engines to power vehicles. Gasoline was chosen almost by default because it was inexpensive and available. In the early days of automobiles, petroleum companies almost could not figure out how to get rid of the gasoline that was left over from the refining
processes. If not for automobiles, who knows what they would have done with all of the gasoline created from the refinement of crude oil.

It should be noted too that since gasoline was first developed for piston engine use, the entire field of organic chemistry was developed and matured. At the same time, techniques and methods for synthetically creating custom made hydrocarbon molecules on demand, has become possible and economically feasible. With these advances it became possible now at the beginning of the 21st century, rather than to take the random assortment of hydrocarbon molecules resulting from the traditional crude oil refining method, custom hydrocarbon molecules can be created to behave as needed. In the case of aviation gasoline, the behaviors of fuel in the aircraft can be closely recreated by creating exactly the hydrocarbon molecule desired.

Over the next two and a half years at Swift, several hundred samples were blended in small quantities and tested in the laboratory and through computer modeling software. Based on the data gathered, Swift would alter the formulation slightly or entirely to produce the desired test result. From 2007 to early 2008 testing began to expand outside of Swift’s laboratories and tests were conducted on small engines at the Delphi Municipal Airport (1I9). In addition to this practical testing, Swift had tests conducted by independent third-party fuel testing labs. These fuels were tested on all of the parameters for leaded aviation gasoline, 100LL. The goal became to find a fuel that matched all the vital performance parameters for 100LL specified in ASTM D910. What started out as a six component fuel, after much testing and verification, soon became a two component mixture which satisfied 98% of the specified performance parameters of ASTM D910 on March 24, 2008. Due to the simplicity of the mixture, Swift personnel knew that it was possible to synthetically create these pure hydrocarbons using sustainable resources. Finally, on April 16, 2008, SwiftFuel Sample 702 was proven to meet all of the critical performance parameters set forth for aviation gasoline by ASTM D910.
SwiftFuel, also referred to as 100SF or UL102, is a binary mixture of pure hydrocarbons. These hydrocarbons are 1,3,5-trimethylbenzene (Mesitylene), an aromatic hydrocarbon, and 2-methylbutane (Isopentane), a branched-chain alkane. They are mixed together in an 80/20 ratio by volume and produce a nominal aviation gasoline with a 104.9 MON capable of emulating nearly all of the performance parameters of ASTM D910, for Grade 100LL. UL102 is completely miscible and fungible with current 100LL in any ratio without falling out of minimum specification for MON (99.6) as set forth by ASTM D910. Testing has shown that 100SF is able to be used as a near-drop-in replacement for 100LL without first having to modify aircraft, engine, or fuel systems. The pure hydrocarbons that comprise 100SF are synthetically manufactured using a biomass input, making the fuel sustainable and renewable.

Swift joined as a member of ASTM International in 2006 with the intention on one day fitting SwiftFuel into the ASTM D910 specification for aviation gasoline, right alongside of 100LL. As the years went by, it became apparent that Subcommittee J02, which governed the specification, would not allow an unleaded fuel to be added into a leaded fuel specification. The Subcommittees intention was to let the D910 specification expire once leaded gasoline for aviation was no longer produced. Despite the change in plans, Swift decided that forming a task group by which to disseminate testing results and data for SwiftFuel would be the best path forward. In early 2008, Swift asked formally that a task force be formed, of industry members, to help move the fuel forward through certification. Throughout the first few task force meetings, it became apparent that the task force would also offer guidance and suggestions of tests to be performed on the fuel to prove its viability as a replacement for 100LL. Through industry collaboration, SwiftFuel was tested and evaluated. at by the following industry players: Lycoming Engines, AvFuel Corporation, The FAA Technical Research Center, Cessna Aircraft Company, Teledyne Continental Motors, Beechcraft Aircraft Company, Embry-Riddle Aeronautical University, Dixie Services (ASTM Test Laboratory), General Aviation Modifications Incorporated (GAMI), Purdue University Aviation Technology Dept., National Institute of Standards and Technology (NIST), and
the United States Air Force Research Labs (AFRL), to name a few. Each subsequent test resulted in what became mini-endorsements for SwiftFuel, by each of the respective organizations, based off of the performance results. With each bit of test data generated, task force members became more convinced of the technical merits of SwiftFuel. The task force leader, a representative of ExxonMobil, suggested that Swift pursue a “Test Fuel Specification” through ASTM. This test specification would ensure that each batch of test fuel produced, complied with an ASTM standard, thus validating each run conducted for final certification. The specification itself would be similar to D910 in that it laid out performance standards to which the fuel must comply with.

Proving the need and technical backing of this test specification would prove to be a huge undertaking. Swift had to prove to the task force and to ASTM that a new specification was warranted and that enough data existed to establish the parameters set forth in the new test specification. The vehicle the task force chose to compile this information, for presentation, was a standard ASTM research report. Swift began compiling all past testing results into a valid ASTM research report. Among the many reports contained within this research report were two studies done by the FAA Technical Research Center. The two reports covered Detonation Mapping & Power Baseline and a Part 33 Engine Endurance test. The Detonation Mapping & Power Baseline concluded that SwiftFuel had a higher detonation margin than the baseline 100LL fuel. It showed that SwiftFuel could stave off detonation in a large-bore high compression Lycoming IO-540 aviation engine. The test showed that an additional three to four inches of MAP were gained before detonation onset (Atwood, Full-Scale Engine Detonation and Power Performance Evaluation of Swift Enterprises 702 Fuel, 2009). The other FAA test, the Part 33 Engine Endurance test, was conducted “to determine whether there were any initial major engine performance-related findings that would prevent further research into the use of a Swift binary blend of these components” (Atwood, FULL-SCALE ENGINE ENDURANCE TEST OF SWIFT ENTERPRISES UL102 FUEL, 2010). Since there existed no lubricity requirement for aviation gasoline, this test was estimated,
by the task force, as the best way to examine any negative long-term effects of removing tetra-ethyl lead (TEL) from aviation gasoline to the engine. “The endurance test results indicated that the engine experienced normal levels of engine wear during the 150-hour test, and combustion, oil, and fuel deposits were light” (Atwood, FULL-SCALE ENGINE ENDURANCE TEST OF SWIFT ENTERPRISES UL102 FUEL, 2010). Based on these tests and nearly 50 others, Swift compiled a 500 page research report for ASTM review. The research report was submitted for ballot by ASTM in September of 2010. In November of 2009, the results from the ballot came back. There were only 2 of 226 voters that voted negative on the report (ASTM International, 2010). This indicated that most of the members of the aviation fuels subcommittee felt the report was warranted. The two negative voters had their issues resolved by Swift at the ASTM meeting in December and subsequently withdrew their negative votes at that time, allowing the ballot to pass.

With regard to the test fuel specification, Swift balloted an initial specification in October 2009 at ASTM, it received three negative votes. Two of the negative votes were editorial changes and were withdrawn to allow the ballot to pass forward. There was however one negative that was unable to be withdrawn to allow the ballot to pass. This negative pointed to the fact that there existed not enough data to prove the necessity of this type of specification. This is the main reason that the above-mentioned research report was balloted; which created a body of data and knowledge on which to base a test fuel specification. Using the data comprised in the successfully balloted research report, a second ballot was issued to ASTM, by Swift, in November 2010. The ballot was a Standard Specification for High Octane Unleaded Test Fuel. The ballot was voted upon by members of the ASTM Subcommittee for Aviation Fuels and received no negative votes, with 100% of the committee participating in the voting. This means that all 250 members of the subcommittee felt that this specification was acceptable and had the necessity of this specification proven through data contained in the research report. This was a huge accomplishment for Swift, as it validated the hard work and nearly five years worth of effort that
had gone into the development of SwiftFuel. The results of both the research report ballot and the Specification were validated at the annual ASTM meeting in December 2010. The specification was allowed to pass to full committee ballot for its final critique before publishing as an official standard.

In February 2011, the final balloting of the specification for UL102 began. When the ballot closed in April 2011 there were only two negative votes that arose. In three days time, the Swift crew worked to make the editorial changes to the specification and allowed for the negatives to be withdrawn by their respective voters. SwiftFuel UL102 was finally covered under a legitimate ASTM standard under ASTM D7719, the Standard Specification for High Octane Unleaded Test Fuel, for Grade UL102 by May 2011. This is the first time, in history, that an unleaded +100MON fuel designed for aviation was certified under a standard ASTM specification.

Beyond the Test Fuel Specification, further testing is required before final certification is achieved for all aircraft. This testing will be accomplished by the individual OEM’s and their partners. This data is once again to be compiled into a final full research report, including the original data and balloted at ASTM. It is planned that the final balloted research report will support the conversion of the test specification to a full final commercial specification. It has been estimated by task force leaders that this process should take only a third of the time to accomplish, as the “heavy lifting” is done with the completion of the test specification. However, a true timeline to completion is merely estimation since a roadmap to completion has not ever before existed. This is due to the fact that a new fuel has not been certified for use in aviation since before the start of World War II. Though it may seem insurmountable at times, the milestones thus far accomplished by Swift demonstrate that it can be done.
Chapter 8

100VLL Aviation Gasoline

When the Clean Air Act was signed into law on December 31, 1970, by President Richard Nixon, the implications for aviation would be felt nearly 40 years later. The Clean Air Act of 1970 and its subsequent revisions in 1990 specifically aimed at reducing the use of tetra-ethyl lead (TEL) in the United States. Beginning with the largest user of TEL in the 1970’s and 80’s, autogas slowly began to phase out the addition of TEL. By the end of the 80’s, lead had pretty much disappeared from autogas, and by 1990 all TEL was banned from use in on-road motor vehicles. The only uses of TEL that remained at the start of the 90’s were for off-road vehicles, recreational vehicles, such as watercraft and snowmobiles, and general aviation. These vehicles operated under special exemption from the Clean Air Act of 1990 as the volume reduction created by removing TEL from auto gasoline served to meet the requirements of the Clean Air Act. However, in January 1996, off-road use of leaded fuels was banned altogether. The only transportation sector that was still allowed to use leaded fuels was general aviation. General aviation continued into the twenty-first century still burning a leaded gasoline, 100LL, under exemption from the Clean Air Act due to safety of flight concerns expressed by the FAA.

By 2011, various environmental groups have put general aviation under great scrutiny as it was the source of 45% of annual domestic lead emissions (Passavant G., 2009). On October 12th, 2006, a petition was filed with the EPA by Bluewater Network, a division of Friends of the Earth, asking the EPA to determine whether lead emissions from general aviation pose a significant risk to human health (Passavant G., 2009). If sufficient information was found, the EPA was asked to make a formal Finding of Endangerment to public health and welfare. This would result in the regulation of lead emissions caused by the combustion of 100LL. The other driving force behind the reduction of 100LL use was the updated National Ambient Air Quality Standard (NAAQS) for lead, which was released by the EPA in
October 2008. For the previous twenty nine years, the limit for ambient air lead was set at 1.5 µg/m³. Medical research since then showed that much smaller lead levels can cause serious health effects, especially in children. The new standard allowed for lead levels to be reduced to only 0.15 µg/m³ of air, or 10% of the old standard, by no later than January 2017 (Passavant G., 2009). If non-compliance was revealed, it became up to the individual states to correct the matter, not the federal government.

This remained the backbone for why the industry sought an unleaded alternative for 100LL. Mike Kraft of Lycoming Engines said it best when he stated the following to a group of pilots at Oshkosh, “The members of the industry prefer to make the decision ourselves [transitioning to a UL fuel], rather than have the government regulate us into one […] we [general aviation] will lose with the latter of the two choices” (Kraft, 2009). It was estimated that nearly 400 airports in the United States would not comply with the new NAAQS standard. EPA monitoring that began at some of those select airports, which began in March 2011, was predicted to show the same non-compliance. During search for an unleaded fuel, industry members and advocacy groups began to propose a temporary solution that would buy these non-compliance airports and their respective states more time before the introduction of an unleaded general aviation replacement fuel. An industry coalition began exploring the feasibility of a “band-aid” fuel to satisfy the near term goals of lead reduction while certifying a replacement unleaded fuel.

In an effort to comply with the new EPA lead limits a new Very Low Lead version of 100 octane fuel has been proposed. This section explores: the composition of 100VLL, the industry players behind its inception, the highlights of the test results on 100VLL, the specification of the fuel, where 100VLL is at today, and the future for the fuel.

The composition of 100VLL is identical to 100LL with one minor alteration in the maximum TEL content. Unlike most of the other fuels examined, 100VLL is not intrinsically different in composition
from the current aviation gasoline. In fact, 100VLL fits within the ASTM D910 specification for leaded aviation gasoline. In December 2009 Grade 100VLL was proposed as an additional grade of fuel to be added right alongside of 100LL in Table 1 of the specification. The composition of the base alkylates used to manufacture 100LL remains unchanged for Grade 100VLL. In most cases 100VLL is a new name for the same 100LL formulation that already populates the general aviation fuel supply currently.

The Coordinating Research Council (CRC) (the research arm of the ASTM) compiled a report investigating the reduced lead content in 100LL and examining the current supply of 100LL for current lead content. One of the major findings of CRC Report 657 was that in relation to current lead content is that, “a reduction [in max TEL content] is technically feasible, [however] there are other non-technical considerations which must be addressed by the aviation industry which are outside the jurisdiction of CRC research” (Wilkinson, 2010). The aim of the survey was to determine if the current 100LL at FBO’s contained the maximum amount of TEL listed in Table 1 of D910. The survey showed that of 89 samples surveyed, which represented 8 total refineries, the mean lead content was 84% of the max (0.56 gPb/L) listed in D910 (Wilkinson, 2010). The industry group initially proposed that all that would be required was a reduction in the maximum TEL content specified, under a new grade, which would require no change to the actual fuel provided. However, even the statistical mean of the fuel sampled indicated that it would not comply with the proposed reduction to 0.45 gPb/L (ASTM International, 2011).

Despite the technical considerations the report mentioned “other non-technical considerations” (Wilkinson, 2010) which needed to be addressed. These issues came to light during the subcommittee and task force meetings at the June 2010 ASTM gathering. The issues that were alluded to resided at the refinery level rather than at the FBO. Several major refiners took exception to the proposed reduction stating that it would require a major change in current refiners setup; thereby, causing a significant
increase in fuel price. It was also mentioned that some refiners currently producing avgas would be unwilling to modify their production process to accommodate 100VLL.

As it is now apparent, current refineries use many different methods to achieve the performance parameters of D910. Each refiner, uses a different quality of alkylate stream, based on what they have available, as a base-stock for avgas. To make up for the low quality of alkylate that some refiners use, they must add more TEL to achieve the requisite octane rating required. When manufacturing 100LL, this becomes a mute point since the final finished product complies with D910. With the reduction in max TEL content, these refiners that have optimized their avgas production are in danger of not being able to produce a compliant 100VLL fuel. Due to the low margins in avgas already it is feared that these refiners may be unwilling to make the investment in infrastructure modifications and or an adjustment to the ratio of different products to produce the same volume of avgas.

Another technical concern that was addressed by industry members was the question of whether or not a minimum MON of 99.6 provided the necessary anti-knock protection required for all current general aviation piston engines. It was explained that the minimum of 99.6 MON established for Grade 100LL was sufficient due to the extra margin of safety afforded by the higher max TEL limit. It was acknowledged that 99.6 MON itself might not be adequate to provide full anti-detonation protection to the entire range of 100LL-certified engines; however, due to the max lead content it was unlikely that a delivered fuel would have a MON of 99.6. In fact the CRC report showed that the mean MON of the surveyed fuels was 103.7 and the minimum found was 101.6 (Wilkinson, 2010). With grade 100VLL, the margin would be reduced nearing the bottom-end limit of 99.6. In the interest of getting Grade 100VLL passed during the current round of ASTM voting, engine-run data was promised if the vote could pass unencumbered.
The group pushing for the inclusion of Grade 100VLL included major aviation advocacy groups comprised of the Experimental Aircraft Association (EAA) and the Aircraft Owners and Pilots Association (AOPA). The general aviation manufacturers were represented by the General Aviation Manufacturers Association (GAMA). Special interest groups were represented on the committee by the National Air Transportation Association (NATA) and the National Business Aviation Association (NBAA). Avgas manufacturers were embodied by the participation of the American Petroleum Institute (API), and the National Petrochemical and Refiners Association (NPRA) on the committee. The sole purpose of the group was to be “actively engaged in working with the manufacturers, the FAA, and the EPA to achieve significant reductions in lead emissions for the General Aviation piston powered fleet which requires a minimum grade 100LL AVGAS” (ASTM International, 2011). Several independent consultants were hired to help provide insight and aid in developing the specification and accompanying CRC Report. The group arrived at Grade 100VLL based on pre-determined criterion of “1) a drop-in reduced TEL content AVGAS as a replacement for grade 100LL, 2) no action required from manufacturers or operators, 3) no impact on engine or aircraft FAA certification, and 4) a lowering of the total lead emissions in airport areas where monitoring may determine the current NAAQS standard is not being met” (ASTM International, 2011).

The final specification for Grade 100VLL has not completed. As of April 2011, the revision of ASTM D910 to include Grade 100VLL in Table 1 was up for ballot at main committee. Providing this revision passes main committee, Grade 100VLL becomes an official grade of avgas under D910. The final minimum TEL content balloted was 0.45 gPb/L; this equated to an 18% reduction from that specified for Grade 100LL (ASTM International, 2011). No other changes to the D910 specification were required. Upon passing of the ballot, Grade 100VLL would technically be available for sale.
The future of Grade 100VLL is somewhat unknown as the specification has not yet passed the main committee. However, Grade 100VLL was not designed to be “the next 100LL” so its implementation system-wide is somewhat unlikely. 100VLL was designed so that the states that have airports which are in non-attainment of the reduced NAAQS standard have method available to show a reduction in lead emissions, without having to restrict air traffic operations. There are still those in the industry however who are cornered that the benefits gained by the use of 100VLL are far outweighed by the possible negative consequences and end-user confusion. A required relabeling of those facilities offering Grade 100VLL would undoubtedly confuse pilots and FBO operators. If pilots do not fully understand that the Grade 100VLL fuel can be used in their aircraft, they may choose to purchase 100LL fuel elsewhere resulting in unsustainable reductions in fuel sales at those FBO’s who are mandated to sell 100VLL. Though technically 100VLL may be sound, the financial implications to refiners, pilots, and FBO’s may not be fully realized until it is too late. As acknowledged by the 100VLL task force themselves, the future relies on the certification and approval of an unleaded replacement for 100LL; thereby, reducing the effective lifespan of Grade 100VLL.
Chapter 9
Aviation Fuels Certification

The certification of aviation gasoline is a multi-step process involving many different entities and organizations. Up to this point, the industry has been primarily centered on the use of a single legacy fuel, 100LL. Fuels that have been certified in the past few decades, such as 82UL, are not capable of replacing the legacy fuel altogether; therefore, designing a recertification process has not been necessary. With the forthcoming fuels’ potential ability to replace 100LL, certification is more important now than it has been in the past. In this chapter examines: the way aviation gasolines have been certified in the past, the ASTM’s role in fuel certification, some issues that exist with certifying new fuels for fleet-wide use, and how it is envisioned that replacement gasolines are to be certified in the future.

In aviation, as with most industries, technological advancements are always being introduced to the market. However, these advancements have not just been hardware and technology advancements, they have also included fuel advancements. As engine and airframe technology improved, so too did the requirements of the fuel to support those advancements. Over the years, the ASTM D910 specification has been continually altered and changed to accommodate the ever changing demand. What has evolved is learned from years of experience and improvements in engine design.

Traditionally, aviation gasoline has been manufactured from crude oil at an oil refinery. Transportation fuels in general are handled as commodities, with avgas having a closed distribution system to deliver fuel to the end user, more so than any other fuel type. As a “commodity” everyone makes the assumption that fuel just “is”. They treat fuel like water, or air, and give little thought to the fact that in order to make aircraft design decisions; fuel must be uniform, dependable, and always the same. The FAA has governance and control over all issues that deal with aviation and safety of flight.
Fuel is included under those auspices; however, the method of its certification is not straightforward. With regard to fuel, the FAA heavily relies on fuel specifications derived from ASTM. The FAA then certifies not the fuel but the engines and airplanes to operate on that specified fuel.

The exact route in which 100LL was allowed to be used for flight originates at the ASTM specification itself. In 1942 the ASTM approved a new grade of aviation fuel, 100/130 avgas, and in 1951 it was approved as part of the new ASTM D910 specification (ASTM Subcommittee D02.J, 1998). This specification would end up the backbone for all leaded aviation gasoline. Because every fuel grade contained within this specification maintained the same performance properties, except for octane numbers, the FAA authorized the use of any fuel grade listed; as long as the minimum octane number specified by the OEM was satisfied. For example and engine certified on Grade 80 could also legally operate on both Grades 91 and 100. Due to rising concern over airborne lead emissions from Grade 100 that stemmed from the research being done leading up to the EPA Clean Air Act, Grade 100 LL was developed, which had a maximum lead content that was one-half that of Grade 100. Since the octane rating of Grade 100LL remained the same as that of Grade 100, all engines and aircraft approved for use on Grade 100 were automatically certified to run on Grade 100LL. After the rollout of 100LL, the industry began a push to streamline aviation gasoline grades. This push inevitably led to the discontinuation of all other grades of leaded avgas in commercial quantities, leaving 100LL as the sole fuel. The only real effect on aviation engines was the requirement that engines certified on Grade 115/145 to be de-rated to run on 100LL.

Certification has been relatively straightforward for the past four decades. New equipment, such as the Cirrus SR-22, was certified by the FAA based on a known fuel, 100LL. In the example of the SR-22, the OEM first had to choose a fuel or fuels on which to certify their aircraft. As 100LL was the only commercially available fuel, ASTM D910 Grade 100LL fuel was chosen. The engine OEM, in this case
Teledyne-Continental Motors, had to certify the engine under an FAA CFR Part 33.7 test. According to the Code of Federal Regulations (CFR’s), this test “establishes operating limitations for [...] fuel grade or specification” (FAA, 2011). Again, the FAA in this case is not certifying a fuel or fuel grade, they are certifying that a fuel meeting the specification is now an operating limitation of the engine under CFR Part 33.7. The next step in certification is the airframe OEM, in this case Cirrus, undergoing a CFR Part 25 certification on the airframe, with the CFR Part 33-certified engine. Under CFR Part 25.1521, the OEM must establish powerplant limitations “so that they do not exceed the corresponding limits for which the engines or propellers are type certificated” (FAA, 2011); one of the subcategories included is fuel specification. This again calls attention back to the ASTM specification under which the grade of fuel was certified, which in this case is of course ASTM D910. One final certification the airframe OEM must undergo, with regard to fuel, is certification under CFR Part 25.1583. This is a section of operating limitations on certified aircraft. Under this part, fuel is established as a true operating limitation. Under this part, it specifies that “Limitations required by Sec. 25.1521” (FAA, 2011), become powerplant, and subsequently airframe, limitations in the Airplane Flight Manual (AFM). The last and final portion of certification which deals with fuel certification is detailed in CFR Part 91.9. This part pertains to the pilot rather than the specific OEM’s. Part 91.9 states that, “no person may operate a civil aircraft without complying with the operating limitations specified in the approved AFM” (FAA, 2011). Again this part adds a further layer, this time it is the responsibility of the pilot in command, to ensure the correct fuel is used.

Many will argue that the FAA should certify new fuels in the same manner that aircraft parts are certified. In the case of new aircraft parts, the FAA has oversight of the entire process. With a new part, engineering drawings are submitted to the FAA and based off of those drawings, the FAA starts with the raw material oversight. Then the FAA ensure the manufacturing process and final installation are all compliant with the original engineering drawings. Essentially the FAA with this method has direct
oversight in every step of the process, with the industry providing data and information for FAA approval. With fuel however, this is nearly impossible. Doing a comparison to the previous example, the engineering drawing in this case is the fuel specification. Then the next major difference is the fact that the industry (i.e. the oil companies and OEM’s) has oversight over the entire process until the fuel is delivered to the end user. This puts the onus on the industry, not the FAA to ensure that raw materials and manufactured product are up to specification. Even “final assembly” and delivery are still in the oversight of the industry. Only when the fuel is pumped into an end users aircraft does the FAA have oversight. The only form of oversight the FAA has at this point is to ensure that the operating limitations, established during aircraft certification are in compliance, through the pilot in command. The entire process of FAA oversight of fuel is completely hinged on the specification, which for the most part is under industry control.

To date, with fuels that comply with ASTM D910, this has not been a problem. New aircraft have been certified on a known fuel. However, as mentioned in previous chapters, D910 is only applicable to leaded petroleum-derived gasolines. Therein lies the problem. The industry desires to move to an unleaded fuel to replace current 100LL. As mentioned above, the FAA does not certify new fuels; therefore, the logical place to start is at ASTM. The ASTM is comprised of committees and subcommittees which are populated by industry members. All liquid transportation fuels fall under the D02 committee on Petroleum Products and Lubricants. Each liquid fuel used for transportation falls under this committee. There is a further subdivision called Subcommittee J0 which handles aviation fuels. Aviation gasolines, such as 10LL, fall under the J0.02 section of subcommittee J02. Based off of the previously reported facts one could assume that the only method by which to certify a new fuel would be to add it to the D910 specification. Unfortunately, it is not that simple. ASTM members maintain that D910 is reserved for only leaded petroleum derived gasolines. Subcommittee members are also very adamant that the fuel contain some amount of TEL. Therefore, stating that a new fuel grade has a TEL
content of 0 is not possible. Though the specification does not give a minimum amount of lead each fuel must contain, D910’s preamble states that the finished fuel must contain TEL. It is the intention of the subcommittee to allow this specification to expire once leaded fuels are no longer available or manufactured; rather than altering it to accommodate unleaded aviation gasolines.

Without the ability to alter the only specification that general aviation aircraft have been certified to since 1951, the only route that remains is to have a new specification issued by ASTM. This presents an entirely new set of hurdles, though, not insurmountable. Currently there exists no set path for new fuels to obtain this certification. This is more than likely due to the fact that a new aviation gasoline, equivalent to the performance of 100LL, has not existed since the inception of the specification in 1951. This means that the subcommittee members are not aware of how to accomplish this task and guidance from ASTM does not exist, as this was not a common occurrence. The path that is now recommended for potential replacement fuels is still somewhat undefined; however, steps have been taken to ensure this guidance exists in the future. Recently the ASTM formed a task force to examine and develop a roadmap to certifying new fuels that come before the subcommittee. This roadmap is a step in the right direction as it attempts to outline every step of the process in certifying a new aviation gasoline. Unfortunately, this guidance is still in process and will take quite some time to finish, ballot, and become approved. For new fuels that are ready for certification now, this guidance may not arrive in time. In the mean time however, new fuels have taken direction from the industry members that comprise the “new guidance task force” so that their path to certification is in line with the new guidance when it is released.

The path to new fuel certification is different for each fuel depending on its properties. With fuels that have equivalent performance properties to 100LL, there exists a basic, sometimes undefined, path for certification. Initially, the group or company that wishes to design a specification for their new
fuel must first approach the J0.02 subcommittee with preliminary data as it relates to D910 and show where it deviates from the current fuel specification. Then a task force forms which focuses on the fuel itself. This task force is open to all members of ASTM that wish to have a working hand in the fuels certification effort. The task force will likely suggest that the fuel providers begin assembling a preliminary research report. This will include things such as: materials compatibility, fuel system tests, limited engine tests, certificates of analysis, and test reports from partner industry testing. This preliminary research report is presented to the task force for editing and comment. When the task force feels that this research report is sufficient, they authorize the balloting of the research report to the subcommittee. The subcommittee has approximately 30 days to vote and comment on the research report. Anything from format to extraneous data can be commented on and voted upon. It is up to the leaders of the task force, usually the fuel petitioners, to handle any negative votes with the voter. The goal is to rectify the negative vote by discussing the issue and making the necessary changes to the report. If a change is needed that is not considered editorial in nature, the ballot must be withdrawn and the research report must be re-balloted all over. If the change required to withdraw the negative vote is editorial in nature, the vote can be changed and the ballot can move forward. Once all comments and negative votes are addressed, and the negatives all withdrawn, the task force lead must present to the full D02 committee the results at their semi-annual meeting.

Once a successful ballot of the preliminary research report is complete, the task force can then prepare a test fuel specification for ballot. The design of this specification should be as close to D910 as practical, with the necessary changes to accommodate the new fuel. The successful preliminary research report ballot should be used as the data set proving the need and viability of the new specification. Again, a similar ballot process is exercised as in the research report. All negatives and issues that arise from the test specification ballot should be addressed, adjudicated, and reported to the D02 committee. Once this process is complete and the ballot is unencumbered from the subcommittee, the ballot must
then move to the main committee for approval. Once it reaches the main committee the ballot begins this back and forth process all over again, as it did in the subcommittee. Upon closing of the ballot at main committee any and all negatives and comments must be addressed. Once again, if a change is required that is not editorial in nature; the ballot must go all the way back to the subcommittee for re-ballot before being put back in front of the main committee. Upon successful adjudication of the main committee ballot, the specification is then put up for society review. This is a final step process allows members from all committees, not just the D02 main committee, to give their input. Usually this is more of a formality than just a back and forth issue. Upon successful completion of the society review, the specification is issued a specification number and published in the ASTM book of standards.

As one can gather, this is a very intense and long process; however, the product that comes out the other side has gone under the microscope of the industry and is a far superior product. This is why the FAA relies so heavily on this process. They acknowledge that this industry consensus process is far better than a handful of FAA personnel in an office examining new fuel certifications. Even the FAA has members on both the subcommittee and main committee which offer the regulatory input to the process. This is far superior a method for certification than the alternatives.

At the completion of this process, further data should be collected to compile a final research report. This research report should be again balloted and adjudicated through both the subcommittee and main committee. It is issued a research report number (RR#) from ASTM. This RR# should be referenced on a further ballot to convert the test specification to a final specification. This ballot must also go through the ballot and adjudication process. Once this happens, the specification process in complete with all of the accompanying data to prove its validity in the record at ASTM.

While nothing is set in stone, the FAA is beginning to envision how replacement gasolines are certified in the future for use fleet-wide. It is clear that there must be some sort of D910 equivalency
approval that can tie a new specification to the existing D910. To examine these possibilities the FAA Administrator has called for the formation of an Unleaded Avgas Transition Aviation Rulemaking Committee (UAT-ARC) in January 2011. The ARC is tasked with designing a method by which new fuels could be equivalently rated and compared to D910 for approval for use. Though this path does not yet exist, some of the methods being developed by the ARC would allow a comparable performance fuel to have a blanket certification without having to recertify each engine and airframe combination. The aforementioned specification route would still allow for the same safety of oversight, by the industry, to assure the fuel complies with the specification. Final oversight is still held by the FAA to ensure that the operating limitations are met. This would also benefit the OEM’s as they would still be able to have a guarantee that a new fuel would be covered by a specification, which is paramount if litigation arises.

Though nothing is finalized, over the past decade the industry and government agencies have taken major steps in ensuring that a future fuel is not mired in unnecessary testing and procedure. The industry now, more than ever, has taken a stance to ensure that new fuels have a roadmap to the finish line which will allow them to bring a fuel to general aviation. Though there are potentially more roadblocks to growing the general aviation sector, this process will ensure that fuel beyond TEL, is not one of them.
Chapter 10
Miscellaneous Aviation Gasolines

This section will attempt to cover the potpourri of other miscellaneous aviation gasolines. It is acknowledged that fuels listed in this section need to be further examined when more data becomes available. Though most aviation gasolines comply with ASTM D910, there are a few foreign grades that do not comply with the ASTM D910. Most of these grades are found in the far reaches of the east, in the former Soviet Union eastern bloc countries and in rural parts of China. There exists little mention of these fuels outside of the Lycoming Service Instruction 1070. This will be the primary reference document for these fuels. The first fuels mentioned in SI1070 were the grades B91/115 and B95/130. The service instruction points out that these fuels “are available for use in the Commonwealth of Independent States (CIS)” (Lycoming Engines, 2010). The Lycoming service instruction advises that the grade B91/115 is most closely related to grade 100LL and colored with a green dye, and grade B95/130 will be amber in color (Lycoming Engines, 2010). However, SI1070 does not call out specifically the lead content of the fuels. The service instruction does however mention that these “fuels are specified by GOST101272 [with] Max. TEL content of 2.5g/kg (B91/115) and 3.1g/kg (B95/130)” (Lycoming Engines, 2010). The specification mentioned is controlled by a Russian standards agency; no English copies were available for further investigation. No further information could be found on these specific fuels in any other manufacturers list of approved fuels.

Another fuel that appears briefly in the assortment of fuels is a specialty fuel available for use in Ukraine. This is a leaded fuel named 91, not to be confused with UL91. Lycoming SI1070, names fuel 91 as an approved fuel in selected engines which will appear Yellow in color (Lycoming Engines, 2010). The service instruction states that the “Ukrainian 91 is specified by TU38.590148196 with Max. TEL content is 2.5g/kg” (Lycoming Engines, 2010). This specification was never found for further reference. With
regard to other fuels, the service instruction mentions that “in some overseas countries, grade 100LL fuel is colored green and designated as ‘100L’” (Lycoming Engines, 2010).

While this is a brief overview of miscellaneous fuels, it is worth mentioning as a point of reference. It is very unlikely that these fuels will be sought as a replacement for 100LL due to their esoteric nature. Nonetheless, it is worth further exploring any available information surrounding these few fuels.
Works Cited


C. Sincock, personal communication. (2008, April 2). West Lafayette, IN.


SPECIFICATION APPENDIX

TENTATIVES


Tentative Specifications for AVIATION GASOLINES

A.S.T.M. Designation: D 910 – 47 T

ISSUED, 1947.

These Tentative Specifications have been approved by the sponsoring committee and accepted by the Society in accordance with established procedures, for use pending adoption as standard. Suggestions for revisions should be addressed to the Society at 1916 Race St., Philadelphia 3, Pa.

Scope

1. (a) These specifications are for the use of purchasing agencies in formulating specifications for purchases of aviation gasoline under contract.

   (b) These specifications define aviation gasoline suitable for some but not all types of spark-ignition aviation engines. Certain equipment or conditions of use may require fuels having other characteristics.

Grades

2. Two grades of aviation gasoline are provided, known as:

   Grade 91–98
   Grade 100–130

General

3. These specifications, unless otherwise provided, prescribe the required properties of aviation gasoline at the time and place of delivery.

4. Aviation gasoline, except as otherwise specified herein, shall consist of blends of refined hydrocarbons derived from crude petroleum, natural gasoline, or blends thereof with synthetic hydrocarbons or aromatic hydrocarbons, or both.

Detailed Requirements

5. The aviation gasoline shall conform to the requirements prescribed in Table I.

Workmanship

6. The aviation gasoline herein specified shall be free from water, sediment, and suspended matter. The odor of the fuel shall not be nauseating or irritating. No substances of known dangerous toxicity under usual conditions of handling and use shall be present except as permitted herein.

Approval

7. Unless otherwise agreed by the vendor and the purchaser, the composition and methods of processing of the
Specifications for Aviation Gasolines (D 910 - 47 T)

Table 1—Detailed Requirements for Aviation Gasoline

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Grade</th>
<th>Test Method</th>
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</thead>
<tbody>
<tr>
<td>1,000 ppm</td>
<td>D 911</td>
<td>Test Method</td>
</tr>
<tr>
<td>2,000 ppm</td>
<td>D 912</td>
<td>Test Method</td>
</tr>
<tr>
<td>3,000 ppm</td>
<td>D 913</td>
<td>Test Method</td>
</tr>
<tr>
<td>4,000 ppm</td>
<td>D 914</td>
<td>Test Method</td>
</tr>
<tr>
<td>5,000 ppm</td>
<td>D 915</td>
<td>Test Method</td>
</tr>
</tbody>
</table>

Specifications for Aviation Gasolines (D 910 - 47 T)

Gasoline shall be substantially the same as that of gasoline which has been approved by the purchaser, or by agencies he specifies, on the basis of full-scale bench and flight tests or flight-service experience. If any basic changes in the fuel composition or methods of processing are made, the vendor shall notify the purchaser who will determine if the changes warrant retesting and reapproval of the fuel.

Retests

8. The type and number of tests to insure conformance with the requirements of these specifications shall be mutually agreed to by the vendor and the purchaser of the aviation gasoline.

Methods of Testing

9. The requirements enumerated in these specifications shall be determined in accordance with the following methods of test:

(a) Knobbe Value (lean rating)—Test Method of Test for Knobbe Characteristics of Aviation Fuels by the Aviation Method (A.S.T.M. Designation: D 640).

(b) Knobbe Value (rich rating)—Test Method of Test for Knobbe Characteristics of Aviation Fuels by the Supercharge Method (A.S.T.M. Designation: D 909).

(c) Color—Color comparison may be made by any suitable apparatus or by visual comparison, using identical transparent containers for the fuel sample and for the appropriate Army-Navy blue or green color standard for maximum intensity and minimum intensity (Note 1). Samples of Army-Navy Aeronautical standards which have been exposed to light for more than 24 hr. shall not be used for this test.

Notes:

1—Standard maximum and minimum intensity Army-Navy Aeronautical Color samples are available in legal and 3-qt. metal containers and may be obtained upon application to the A.S.T.M. Corporation, 1916 Easton Ave., New York 17, N.Y. Requests for such samples shall include the following information: identification of a legal standard size color, and whether contents are contained in a 12 or 3-qt. metal container (closed and coppered address).


2. Net Heat of Combustion—The net heat of combustion at constant volume (higher or gross value) shall be determined in a high-pressure calorimeter. Any suitable procedure may be employed provided its accuracy is recognized by the purchasing or supplying agency as being equal or superior to that of A.S.T.M. Method D 380. Test for Thermal Value of Fuel Oil, suitably modified for use with volatile liquids (Note 2). The gross heat of combustion as determined shall be corrected, if necessary, to 25 C. (77 F.) by adding to R a quantity equal to "1.6 (T - 20)," where T is the final temperature in degrees Centigrade. The net heat of combustion shall be calculated from the gross heat of combustion as follows:

Net heat of combustion, Btu per lb. = 3,010 + (0.1015 X gross heat of combustion)


spherical in shape, 3 5/6 in. in diameter, 15 1/2 in. in depth, with a capacity of 156 to 160 lb, and usually weighing 50 to 60 lb. The edge of the dish shall be plain and not bended.

Steam bath—A circular copper steam bath shall be employed, of the type shown in Fig. 1. The bath shown in Fig. 1 allows 10 determinations to be made simultaneously, but smaller baths of the same type of construction may be employed. The openings for the dishes are 35/6 in. in diameter and are round to true circular form, which may be accomplished by means of a large file and emery cloth. This ensures that the dishes will be exposed to steam over all of the surface covered by the gasoline sample and also prevents any steam leaks around the dishes, which is important. Close-fitting covers shall be provided for each opening so that the bath may be used with less than the full number of openings. Fig. 1 shows the tafle which measures even distribution of steam, the opening for a thermometer, and the vent for excess steam which should be at least 12 in. in height. The steam bath shall be mounted in a hood which can be tightly closed. Section shall be provided to remove gasoline vapors and to insure an even distribution of air through the hood. If a fan is used to provide suction, the motor driving it should be of the induction type. It has been found possible to obtain a dependable draft through the hood by installing a 2 in. high-pressure air line in the stack of the vent. The end of the stack is connected to a mercury manometer on the low-pressure side of the control valve. The arrangement acts as a large venturi and gives almost direct air flow through the hood to make "air flow" over each dish uniform, 1 in. holes are bored in the bottom of the hood opposite the opening for each dish, and centered 2 in. from the side of the steam bath. Slipper of 3 in. pipe are placed in a vertical position in the openings, and exit is directed to the top of the slips. These slippers extend to approximately 3 in. above the top of the steam bath, and the exit are set so that the stream of air flowing through them is tangent to the steam bath, thereby setting up a uniform "swirl" of air which tends to eliminate convection effects noticeable in some boxes.

Electric oven—An electric oven capable of maintaining a constant temperature in the range from 100 to 165°C is required.

Balance—An analytical balance sensitive to at least 0.5 mg is required for weighing the copper dishes.

Preparation of copper dishes—The cleaning of the copper dish is probably the most important variable in the entire procedure for the determination of gasoline by this method. Any residue left in the dish from a previous determination shall be thoroughly removed by solution in acetone after which the dish shall be polished with a fine grade of Hornstein wheel. Polishing may be done by hand or with a buffing wheel, but in all cases the surface must be entirely free from any discoloration. The dish may be transferred to a deoxidizer and cooled to room temperature.

Determination of gasoline content—After the polished handling and cleaning of the dish, the weight of the polished dish, using a pestle, a copper dish as a base. Place the dish in an opening in the steam bath, which should be at room
temperature. Measure exactly 100 ml of the gasoline to be tested into a clean, dry 100-ml graduated cylinder and then pour into the dish.

After the sample has been introduced, turn the steam on slowly and maintain it at a low rate for several minutes. This preliminary slow evaporation rate is employed to prevent mechanical loss of gasoline through entrainment of liquid particles due to breaking bubbles, which are formed initially with very volatile products. After the initial boiling subsides, turn the steam on until a small quantity is seen escaping from the vent and the temperature of the bath is between 95.5 and 100°C (211 to 212°F). Maintain this temperature during the course of the evaporation, and continue until no more volatile matter remains in the dish. This usually requires from 2 to 3 hr. for most commercial motor gasoline, and 40 to 60 min. for most aviation gasoline. Then remove the dish from the bath, dry on the outside with a clean cloth, and place in the electric oven at 100 to 105°C for 30 min. Transfer the dish to a desiccator, cool, and weigh to the nearest milligram, using a copper dish as a base, as in the original weighing. Report the increase in weight of the dish as the copper-dish gauze content of the sample in milligrams per 100 ml.

(5) Repeatability—The most important factors in obtaining reproducible results are as follows:

1. Size of the surface of the dish.
2. The surface of the dish must be perfectly clean, as dishes which are slightly tarnished or have any trace of gas from a preceding determination may give results two to three times as high as those from properly cleaned dishes.
3. Time of evaporation—The time of evaporation is affected by the rate of steam flow and by air circulation over the dish. Both of these factors should be controlled. The former can be checked by using just enough steam to keep the temperature constant as indicated by the thermometer. The latter should be regulated in such a manner that a reproducible draft can be established in the hood. No absolute value for the volume of air to be drawn through the hood in unit time has been established and probably need not be set within very close limits. Where the presence of high boiling material requires more than 4 hr. for evaporation, results are more difficult to check from day to day.

(a) Potential Gum.—Tentative Method of Test for Oxidation Stability of Aviation Gasoline (Potential Gum Method) (A.S.T.M. Designation D 872) except that wherever the letter "K" occurs (referring to oxidation time) insert the number 5, designating the number of hours prescribed in these specifications.

(b) Visible Lead Precipitate—If in Section 7 (2) of A.S.T.M. Method D 872 a visible lead precipitate is observed, proceed as follows: Filter the oxidized gasoline through a clean, dry, weighed.tinned-glass crucible and save the filtrate. Wash the bottom of the lead wire twice with fresh 10-ml portions of solvent to remove any incoherent gum or lead precipitate. Filter the washings through the crucible and add the filtrate to the filtered oxidized sample. To ensure homogeneity, mix the contents of the crucible thoroughly and reserve for test. Wash any visible precipitate remaining in the glass liner with additional solvent. Collect the precipitate in the crucible, but discard the wash liquid. Dry the crucible at 302°F (150°C) in an oven for 1...
A Dewar cylinder is employed for holding the cooling liquid or mixture (Note 4). The top of this cylinder is covered with a loosely fitting brass cap containing appropriate openings for the double-walled container. A frame is suspended from the brass cap to hold the double-walled container.

![Diagram of Dewar cylinder setup](image)

**FIG. 2—Apparatus for Determination of Freezing Point of Gasoline.**

**Specifications for Aviation Gasoline (D 910 - 47 T)**

Note 3.—With the apparatus shown in Fig. 1, the rate of melting can be controlled conveniently by reducing the air pressure in the annulus space between the walls of the specimen container. The required reduction in pressure depends upon the nature of the cooling medium, the degree of purity of the latter, and the contact between the inner wall of the container and the cooling medium, and upon the freezing point temperature.

If the freezing-point apparatus is used as a test for boiling point determination, the following procedure is recommended: Place the container in the beaker holder and insert into the Dewar cylinder partially filled with the cooling medium. Stir the gasoline continuously until a temperature is reached at which crystals separate or until the thermometer indicates a temperature of -60°C. In this latter case, record the freezing point as -60°C.

If a freezing point is observed, allow the gasoline to warm up to a temperature of about 10°C above the observed value, the double-walled container being removed for this purpose from the Dewar cylinder. During this warming-up process, stir the gasoline in order to insure uniformity of temperature throughout and to insure melting of the separated solid. Reinsert the container in the Dewar cylinder, and control the rate of heat interchange so that the temperature of the gasoline, while being thoroughly stirred, remains at a rate not in excess of 2°C per min. Record as the freezing point the temperature at which crystals first appear (Note 5).

**Fig. 1** shows the general arrangement of the apparatus. In the diagram, the beaker holder and Dewar cylinder have been omitted for clarity.

**Note 4.—**Any convenient cooling liquid or mixture may be used. A mixture of solid carbon dioxide and gasoline is suitable for liquid nitrogen, should be stored in a cool place.

**Note 5.—**A crystals will appear at the freezing point at a constant temperature higher than the freezing point. This is due to the separation of small amounts of water or ice in the gasoline and should be ignored.
Designation: D910 – 07a

Standard Specification for Aviation Gasolines

This standard is issued under the fixed designation D910; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reaffirmation. A superscript epsilon (ε) indicates an editorial change since the last revision or reaffirmation.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This specification covers formulaulating specifications for purchases of aviation gasoline under contract and is intended primarily for use by purchasing agencies.

1.2 This specification defines specific types of aviation gasoline for civil use. It does not include all gasoline satisfactory for reciprocating engines. Certain equipment or conditions of use may permit a wider, or require a narrower, range of characteristics than is shown by this specification.

2. Referenced Documents

2.1 ASTM Standards:

D 66 Test Method for Distillation of Petroleum Products at Atmospheric Pressure
D 93 Test Methods for Flash Point by Pensky-Martens Closed Cup Tester
D 130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test
D 323 Test Method for Vapor Pressure of Petroleum Products (Reid Method)
D 357 Method of Test for Knock Characteristics of Motor Fuels Below 100 Octane Number by the Motor Method
D 381 Test Method for Gum Content in Fuels by Jet Evaporation
D 514 Method of Test for Knock Characteristics of Aviation Fuels by the Aviation Method
D 673 Test Method for Oxidation Stability of Aviation Fuels (Potential Residue Method)
D 909 Test Method for Supercharge Rating of Spark-Ignition Aviation Gasoline
D 1094 Test Method for Water Reaction of Aviation Fuels
D 1266 Test Method for Sulfur in Petroleum Products (Lamp Method)
D 1298 Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
D 1482 Method of Test for Knock Characteristics of Motor Fuels Above 100 Octane Number by the Motor Method
D 2336 Test Method for Freezing Point of Aviation Fuels
D 2392 Test Method for Color of Dyed Aviation Gasolines
D 2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry
D 2824 Test Methods for Electrical Conductivity of Aviation and Distillate Fuels
D 2700 Test Method for Motor Octane Number of Spark-Ignition Engine Fuel
D 3338 Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
D 3341 Test Method for Lead in Gasolineolene Monochloride Method
D 4052 Test Method for Density and Relative Density of Liquids by Digital Density Meter
D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products
D 4171 Specification for Fuel System Icing Inhibitors
D 4177 Practice for Automatic Sampling of Petroleum and Petroleum Products
D 4306 Practice for Aviation Fuel Sample Containers for Tests Affected by Trace Contamination
D 4529 Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
D 4809 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)

* This specification is under the jurisdiction of ASTM Committee D02 on Petroleum Products and Lubricants and is the direct responsibility of Subcommittee D02.R02 on Aviation Gasoline.

* For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard’s Document Summary page on the ASTM website.

*A Summary of Changes section appears at the end of this standard.
D 4865 Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems
D 5006 Test Method for Measurement of Fuel System Icing Inhibitors (Ether Type) in Aviation Fuels
D 5059 Test Methods for Lead in Gasoline by X-Ray Spectroscopy
D 5190 Test Method for Vapor Pressure of Petroleum Products (Automatic Method)
D 5191 Test Method for Vapor Pressure of Petroleum Products (Mini Method)
D 6460 Guide for Microbial Contamination in Fuels and Fuel Systems
E 29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

3. Terminology

3.1 Definitions:

3.1.1 aviation gasoline, n—gasoline possessing specific properties suitable for fueling aircraft powered by reciprocating spark ignition engines.

3.1.1.1 Discussion—Principal properties include volatility limits, stability, detonation-free performance in the engine for which it is intended, and suitability for low temperature performance.

4. General

4.1 This specification, unless otherwise provided, prescribes the required properties of aviation gasoline at the time and place of delivery.

5. Classification

5.1 Four grades of aviation gasoline are provided, known as:

- Grade 80
- Grade 90
- Grade 100
- Grade 100LL

NOTE 1—The above grade names are based on their octane/performance numbers as measured by the now obsolete Test Method D 614 (Discontinued 1970). A table for converting octane/performance numbers obtained by Test Method D 2700 motor method into aviation ratings was last published in Specification D 910-94 in the 1995 Annual Book of ASTM Standards, Vol 03.01.

5.2 Grades 100 and 100LL represent two aviation gasolines identical in antiknock quality but differing in maximum lead content and color. The color identifies the difference for engines that have a low tolerance to lead.


5.3 Although the grade designations show only a single octane rating for each grade, they must meet a minimum lead mixture rating and a minimum total mixture supercharge rating (see X1.2.2).

6. Materials and Manufacture

6.1 Aviation gasoline, except as otherwise specified in this specification, shall consist of blends of refined hydrocarbons derived from crude petroleum, natural gasoline, or blends, thereof, with synthetic hydrocarbons or aromatic hydrocarbons, or both.

6.2 Additives—Mandatory, shall be added to each grade of aviation gasoline in the amount and of the composition specified in the following list of approved materials.

6.2.1 Tetraethyl Lead, shall be added in the form of an antiknock mixture containing not less than 61 mass % of tetraethyl lead and sufficient ethylene dibromide to provide two bromine atoms per atom of lead. The balance shall contain no added ingredients other than kerosine, an approved oxidation inhibitor, and blue dye, as specified herein. The maximum concentration limit for each grade of gasoline is specified in Table 1.

6.2.1.1 If mutually agreed upon by the fuel producer and additive vendor, tetraethyl lead antiknock mixture may be diluted with 20 mass % of a mixed aromatic solvent having a minimum flash point of 60°C according to Test Methods D 93 when the product is to be handled in cold climates. The TEL content of the dilute product is reduced to 49 mass %, so that the amount of antiknock additive must be adjusted to achieve the necessary lead level. The dilute product still delivers two bromine atoms per atom of lead.

6.2.2 Dyes—The maximum concentration limits in each grade of gasoline are specified in Table 1.

6.2.2.1 The only blue dye that shall be present in the finished gasoline shall be essentially 1,4-dialkylanilinoanthraquinone.

6.2.2.2 The only yellow dyes that shall be present in the finished gasoline shall be essentially p-diethylaminolaurobenzene (Color Index No. 11021) or 1,3-benzenediol 2,4-bis [(alkylphenyl)azo]-.

6.2.2.3 The only red dye that shall be present in the finished gasoline shall be essentially alkyl derivatives of azobenzene-4-azo-2-naphthol.

² Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR: D02.1255.
### TABLE 1 Detailed Requirements for Aviation Gasolines

<table>
<thead>
<tr>
<th>Grade</th>
<th>Grade 90</th>
<th>Grade 87</th>
<th>Grade 100</th>
<th>Grade 100ELL</th>
<th>Grade 90</th>
<th>ASTM Test Method</th>
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<tr>
<td>Octane Rating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knock: max, base mixture</td>
<td>87.4</td>
<td>90.0</td>
<td>99.6</td>
<td>99.6</td>
<td>D 2700</td>
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<tr>
<td>Motor Octane Number</td>
<td>80.0</td>
<td>91.0</td>
<td>100.0</td>
<td>100.0</td>
<td>D 2700</td>
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<tr>
<td>Aviation Laminating Rating</td>
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<td>100.0</td>
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<tr>
<td>Toluene Solvent, ml</td>
<td>0.13</td>
<td>0.53</td>
<td>0.53</td>
<td>1.06</td>
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<td>Maximum Load, g/l</td>
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<td>2.7</td>
<td>2.7</td>
<td>D 3341 or D 5059</td>
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<tr>
<td>Color</td>
<td>Ref</td>
<td>Brown</td>
<td>Blue</td>
<td>Green</td>
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<td>Blue, mg/L</td>
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<td>none</td>
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<tr>
<td>Yellow, mg/L</td>
<td>max</td>
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<td>none</td>
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<tr>
<td>Red, mg/L</td>
<td>max</td>
<td>2.3</td>
<td>2.7</td>
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<tr>
<td>Orange, mg/L</td>
<td>max</td>
<td>none</td>
<td>6.0</td>
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</table>

### Requirements for All Grades

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<tr>
<th>Property</th>
<th>Grade 80</th>
<th>Grade 90</th>
<th>Grade 100</th>
<th>Grade 100ELL</th>
<th>Grade 90</th>
<th>ASTM Test Method</th>
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</thead>
<tbody>
<tr>
<td>Density at 15°C, kg/m³</td>
<td>Report</td>
<td>Report</td>
<td>Report</td>
<td>Report</td>
<td>D 1258 or D 4052</td>
<td></td>
</tr>
<tr>
<td>Distillation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial boiling point, °C</td>
<td>75</td>
<td>75</td>
<td>105</td>
<td>135</td>
<td>D 66</td>
<td></td>
</tr>
<tr>
<td>Fuel Evaporated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 volume % at °C</td>
<td>max</td>
<td>97</td>
<td>80</td>
<td>135</td>
<td>D 303 or D 5190</td>
<td></td>
</tr>
<tr>
<td>40 volume % at °C</td>
<td>min</td>
<td>1.8</td>
<td></td>
<td></td>
<td>40.0</td>
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</tr>
<tr>
<td>50 volume % at °C</td>
<td>max</td>
<td></td>
<td></td>
<td></td>
<td>40.0</td>
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<td>90 volume % at °C</td>
<td>max</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>D 2270</td>
<td></td>
</tr>
<tr>
<td>Final boiling point, °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum of 10% + 50% evaporated temperatures, °C</td>
<td>min</td>
<td>135</td>
<td>135</td>
<td>135</td>
<td>D 2270</td>
<td></td>
</tr>
<tr>
<td>Recovery volume %</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Residue volume %</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss volume %</td>
<td>max</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
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<td>Vapor pressure, 38°C, kPa</td>
<td>max</td>
<td>38.0</td>
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<td>Freezing point, °C</td>
<td>max</td>
<td>40.0</td>
<td>40.0</td>
<td>40.0</td>
<td>D 2270</td>
<td></td>
</tr>
<tr>
<td>Sulfur, mass %</td>
<td>max</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>D 2270</td>
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<tr>
<td>Net heat of combustion, MJ/kg</td>
<td>min</td>
<td>43.5</td>
<td>43.5</td>
<td>43.5</td>
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<tr>
<td>Corrosion, copper strip, 2 h at 100°C</td>
<td>max</td>
<td>No. 1</td>
<td>No. 1</td>
<td>No. 1</td>
<td>D 4297</td>
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<tr>
<td>Oxidation stability (6 h aging)</td>
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<tr>
<td>Piston ring gum, mg/100 mL</td>
<td>max</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>D 2270</td>
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<tr>
<td>Lead precipitate, mg/100 mL</td>
<td>max</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>D 1054</td>
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<tr>
<td>Water reaction</td>
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</tr>
<tr>
<td>Volume change, mL</td>
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<td>±2</td>
<td>±2</td>
<td>±2</td>
<td>D 2624</td>
<td></td>
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<tr>
<td>Electrical conductivity, pS/m</td>
<td>max</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>D 2624</td>
<td></td>
</tr>
</tbody>
</table>

---

*For compliance of test results against the requirements of Table 1, see 7.2.

1 Knock value shall be reported as MON.
2 The test methods indicated in this table are referred to in Section 11.
3 A performance number of 120.0 is equivalent to a knock value determined using iso-octane plus 0.34 ml TEL/L.
4 Knock ratings shall be reported to the nearest 0.1 octane/performance number.
5 The maximum dye concentrations shown do not include solvent in dye supplied in liquid form.
6 Test Method D 5111 shall be the reference vapor pressure method.
7 Test Method D 5111 shall be the reference vapor pressure method.
8 Test Method D 4800 shall be used.
9 If mutually agreed upon between the purchaser and the supplier, a 16 h aging gum requirement may be specified instead of the 1 h aging gum test; in such cases the gum content shall not exceed 10 mg/100 mL and the visible lead precipitate shall not exceed 4 mg/100 mL. In such fuel the permissible antioxidant shall not exceed 24 mg/L.
10 Test Method D 381: assistant gum test can provide means of detecting quality deterioration or contamination, or both, with heavier products following distribution from refinery to airport. Refer to X 1.7.1.
11 Apply only when an electrical conductivity additive is used; when a customer specifies fuel containing conductivity additive, the following conductivity limits shall apply under the condition at point of use:
- Minimum 50 pS/m
- Maximum 500 pS/m.

The supplier shall report the amount of additive added.
6.2.2.4 The only orange dye that shall be present in the finished gasoline shall be essentially benzene-azo-2-naphthol (Color Index No. 12055).

6.3 Additives—These may be added to each grade of aviation gasoline in the amount and of the composition specified in the following list of approved materials. The quantities and types shall be declared by the manufacturer. Additives added after the point of manufacture shall also be declared.

6.3.1 Antioxidants—The following oxidation inhibitors may be added to the gasoline separately, or in combination, in total concentration not to exceed 12 mg of inhibitor (not including weight of solvents) per litre of fuel.

6.3.1.1 2,6-dimethylnaphthalene.
6.3.1.2 2,4-dimethyl-6-tertiary butylphenol.
6.3.1.3 2,4-dimethyl-6-tertiary butylphenol.
6.3.1.4 75 % minimum 2,6-dimethylnaphthalene plus 25 % maximum mixed tertiary and triteriary butylphenols.
6.3.1.5 75 % minimum di- and tri-isopropyl phenols plus 25 % maximum di- and tri-tertiary butylphenols.
6.3.1.6 72 % minimum 2,4-dimethyl-6-tertiary butylphenol plus 28 % maximum monomethyl and dimethyl tertiary butylphenols.

6.3.1.7 N,N'-di-isopropyl-para-phenylenediamine.
6.3.1.8 N,N'-di-sec-ethyl-para-phenylenediamine.
6.3.2 Fuel System Icing Inhibitor (FSII)—One of the following may be used.

6.3.2.1 2-Propenyl Alcohol (IPA, prop-2-ol), in accordance with the requirements of Specification D 4171 (Type II). May be used in concentrations recommended by the aircraft manufacturer when required by the aircraft owner/operator.

Note 3—Addition of isopropyl alcohol (IPA) may reduce knock ratings below minimum specification values (see X1.2.4). The test method D 5006 can be used to determine the concentration of Di-EGME in aviation fuels.

6.3.3 Electrical Conductivity Additive—Stadi 4507 in concentrations up to 3 mg/l is permitted. When loss of fuel conductivity necessitates re-treatment with electrical conductivity additive, further addition is permissible up to a maximum cumulative level of 5 mg/l of Stadi 450.

6.3.4 Corrosion Inhibitor Additive—The following corrosion inhibitors may be added to the gasoline in concentrations not to exceed the maximum allowable concentration (MAC) listed for each additive.

<table>
<thead>
<tr>
<th>Additive</th>
<th>MAC, g/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCI 1a</td>
<td>22.5</td>
</tr>
<tr>
<td>DGI 4a</td>
<td>22.5</td>
</tr>
<tr>
<td>HITEC 680</td>
<td>22.5</td>
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<tr>
<td>NALCO 5403</td>
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</tr>
<tr>
<td>TOLAB 4410</td>
<td>22.5</td>
</tr>
</tbody>
</table>

7. Detailed Requirements

7.1 The aviation gasoline shall conform to the requirements prescribed in Table 1.

7.2 Test results shall not exceed the maximum or be less than the minimum values specified in Table 1. No allowance shall be made for the precision of the test methods. To determine the conformance to the specification requirements, a test result may be rounded to the same number of significant figures as in Table 1 using Practice E 229. Where multiple determinations are made, the average result, rounded according to Practice E 229, shall be used.

8. Workmanship, Finish and Appearance

8.1 The aviation gasoline specified in this specification shall be free from undissolved water, sediment, and suspended matter. The odor of the fuel shall not be nauseating or irritating. No substances of known dangerous toxicity under usual conditions of handling and use shall be present except as permitted in this specification.

9. Sampling

9.1 Because of the importance of proper sampling procedures in establishing fuel quality, use the appropriate procedures in Practice D 4057 or Practice D 4177.

9.1.1 Although automatic sampling following Practice D 4177 may be useful in certain situations, initial refinery specification compliance testing shall be performed on a sample taken following procedures in Practice D 4057.

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1. Supporting data (guidelines for the approval or disapproval of additives) have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR-202-112.

2. Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR-102-1526.

7. Stadi is a registered trademark marketed by Octel America, Inc., Newark, DE 10702.
9.2 A number of aviation gasoline properties, including copper corrosion, electrical conductivity, and others are very sensitive to trace contamination which can originate from sample containers. For recommended sample containers, refer to Practice D 4306.

10. Reports
10.1 The type and number of reports to ensure conformance with the requirements of this specification shall be mutually agreed to by the purchaser and the supplier of the aviation gasoline.

11. Test Methods
11.1 The requirements enumerated in this specification shall be determined in accordance with the following ASTM test methods:
   11.1.1 Knock Value (Lean Rating)—Test Method D 2700.
   11.1.2 Knock Value (Rich Rating)—Test Method D 909.
   11.1.3 Tetraethyllead—Test Methods D 3241 or D 5059.
   11.1.4 Color—Test Method D 2392.
   11.1.5 Density—Test Methods D 1298 or D 4052.
   11.1.6 Distillation—Test Method D 86.
   11.1.7 Vapor Pressure—Test Methods D 223, D 5190, or D 5191.
   11.1.8 Freezing Point—Test Method D 2386.
   11.1.9 Sulfur—Test Methods D 1266 or D 2622.
   11.1.10 Net Heat of Combustion—Test Methods D 4529 or D 3338.
   11.1.11 Corrosion (Copper Strip)—Test Method D 130, 2 h test at 100°C in bomb.
   11.1.12 Potential Gum and Visible Lead Precipitate—Test Method D 873 except that wherever the letter X occurs (referring to oxidation time) insert the number 5, designating the number of hours prescribed in this specification.
   11.1.14 Electrical Conductivity—Test Methods D 2624.

12. Keywords
12.1 Avgas; aviation gasoline; gasoline

APPENDIX

(Nonmandatory Information)

XI. PERFORMANCE CHARACTERISTICS OF AVIATION GASOLINES

XI.1 Introduction
XI.1.1 Aviation gasoline is a complex mixture of relatively volatile hydrocarbons that vary widely in their physical and chemical properties. The engines and aircraft impose a variety of mechanical, physical, and chemical environments. The properties of aviation gasoline (Table XI.1) must be properly balanced to give satisfactory engine performance over an extremely wide range of conditions.

XI.1.2 The ASTM requirements summarized in Table 1 are quality limits established on the basis of the broad experience and close cooperation of producers of aviation gasoline, manufacturers of aircraft engines, and users of both commodities. The values

<table>
<thead>
<tr>
<th>Performance Characteristics</th>
<th>Test Methods</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion characteristics</td>
<td>knock value (lean mixture)</td>
<td>XI.2.4</td>
</tr>
<tr>
<td>Antiknock quality and antiknock compound identification</td>
<td>knock value (rich mixture)</td>
<td>XI.2.5</td>
</tr>
<tr>
<td></td>
<td>isopropyl alcohol</td>
<td>XI.2.6</td>
</tr>
<tr>
<td></td>
<td>tetraethyllead</td>
<td>XI.2.7</td>
</tr>
<tr>
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<td>dyes</td>
<td>XI.2.8</td>
</tr>
<tr>
<td>Fuel manufacturing and aircraft range</td>
<td>density</td>
<td>XI.2.1</td>
</tr>
<tr>
<td></td>
<td>net heat of combustion</td>
<td>XI.3.2</td>
</tr>
<tr>
<td>Carburation and fuel vaporization</td>
<td>vapor pressure</td>
<td>XI.4.1</td>
</tr>
<tr>
<td></td>
<td>distillation</td>
<td>XI.4.9</td>
</tr>
<tr>
<td>Corrosion of fuel system and engine parts</td>
<td>copper strip corrosion</td>
<td>XI.6.1</td>
</tr>
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<td>sulfur content</td>
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<td>Fluidity at low temperatures</td>
<td>freezing point</td>
<td>XI.6.6</td>
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<tr>
<td>Fluid cleanliness, handling, and storage stability</td>
<td>water reaction</td>
<td>XI.7.6</td>
</tr>
<tr>
<td></td>
<td>at storage</td>
<td>XI.7.3</td>
</tr>
</tbody>
</table>


given are intended to define aviation gasoline suitable for most types of spark-ignition aviation engines; however, certain equipment or conditions of use may require fuels having other characteristics.

X1.1.3 Specifications covering antiknock quality define the grades of aviation gasoline. The other requirements either prescribe the proper balance of properties to ensure satisfactory engine performance or limit components of undesirable nature to concentrations so low that they will not have an adverse effect on engine performance.

X1.2 Combustion Characteristics (Antiknock Quality and Antiknock Compound Identification)

X1.2.1 The fuel-air mixture in the cylinder of a spark-ignition engine will, under certain conditions, ignite spontaneously in localized areas instead of progressing from the spark. This may cause a detonation or knock, usually inaudible in aircraft engines. This knock, if permitted to continue for more than brief periods, may result in serious loss of power and damage to, or destruction of, the aircraft engine. When aviation gasoline is used in other types of aviation engines, for example, certain turbine engines where specifically permitted by the engine manufacturer, knock or detonation characteristics may not be critical requirements.

X1.2.2 Aviation gasoline grades are also identified by two numbers separated by a slant line (/). The first number is called the lean mixture rating and the second number is called the rich mixture rating. This specification describes four grades of aviation gasoline as follows: 80/87, 91/98, 100/130, and 100/130LL. Numbers below 100 are octane numbers, while numbers above 100 are performance numbers. At 100, octane number and performance number are equal. The suffix LL describes a grade containing lower tetraethyllead than a second grade of identical lean and rich mixture ratings.

X1.2.3 Both the lean mixture rating and the rich mixture rating are determined in standardized laboratory knock test engines that are operated under prescribed conditions. Results are expressed as octane numbers up to 100 and above this point as quantities of tetraethyllead added to isoctane (2,2,4-trimethylpentane). Octane number is defined arbitrarily as the percentage of isoctane in that blend of isoctane and n-heptane that the gasoline matches in knock characteristics when compared by the procedure specified. The quantities of tetraethyllead added to isoctane that the gasoline matches in knock characteristics when compared by the procedure specified may be converted to performance numbers by a chart. The performance number is an indication of the relative power obtainable from an engine as compared with operation of the same engine with leaded isoctane, operating at equal knocking intensity. The lean mixture rating together with the rich mixture rating can be used as a guide to the amount of knock-limited power that may be obtained in a full-scale engine under cruise (lean) and take-off (rich) conditions.

X1.2.4 It has been observed that when isopropyl alcohol (IPA) is added to a Grade 100 or Grade 100LL aviation gasoline as a fuel system icing inhibitor, the antiknock rating of the fuel may be reduced. Since isopropyl alcohol is normally added in the field at the point of use, the operator is cautioned that performance numbers on the alcohol-fuel blend may not meet specification minimums. Typical performance number reductions with addition of one volume % IPA have been 0.5 motor octane number on the lean rating and 3.0 to 3.5 performance number on the rich rating. Thus a Grade 100 or 100LL aviation gasoline rated in the knock test engines at the point of manufacture to be 99.5/130 octane/performance number might, with the addition of one volume % alcohol, be about 99/127 octane/performance number. At three volume %, the reductions are about 1.5 octane number and 7.5 performance number for lean and rich ratings, respectively. It should be noted that a survey conducted by the General Aviation Manufacturers Association failed to find field evidence or experience to suggest that these reductions have caused engine distress, that is, knocking or power loss at their recommended 1 % maximum level. On Grade 80 aviation gasoline, addition of the IPA additive may increase the octane rating.

X1.2.5 Knock Value, Lean Mixture Rating (Test Method D 2700)—The specification parameter knock value, lean value mixture lists both “Motor Octane Number” (MON) and “Aviation Lean,” as determined by Test Method D 2700. Historically, aviation lean ratings were determined (from 1941 through 1970) by Test Method D 614. An extensive comparison of National Exchange Group data from 1947 through 1964 established that motor octane numbers as determined by Test Methods D 357 and D 1948 could be converted to equivalent Test Method D 614 ratings. A table to convert MON to the corresponding aviation lean rating was included in Test Method D 2700, which was first issued in 1968 as a revision, consolidation and intended eventual replacement of Test Methods D 357 (Withdrawn 1969), D 614 (Withdrawn 1970), and D 1948 (Withdrawn 1968). Currently “Aviation Lean” ratings are only determinable from the MON conversion table in Test Method D 2700. However, the equivalent “Aviation Lean” rating is maintained as a specified parameter in Table 1 to ensure aircraft compliance with historical type certification data sheets.

X1.2.6 Rich Mixture Rating (Supercharge Test Method D 909)—This test method uses a laboratory engine that is capable of being operated at varying air-fuel mixtures and through a range of supercharge manifold pressures. The rating of a fuel is determined by comparing its knock-limited power with those for bracketing blends of reference fuels under standard operating conditions. The rating is made at the rich peak of the mixture response curve (about 0.11 fuel-air ratio) of the lower bracketing reference fuel.

X1.2.7 Tetraethyllead—Tetraethyllead offers the most economical means of providing high antiknock value for aviation gasoline. It is added to aviation gasoline in the form of a fluid which, in addition to tetraethyllead, contains as organic halide scavenging agent and an identifying blue dye. The scavenging agent is needed to keep the tetraethyllead combustion products volatile so that they will theoretically be completely discharged from the cylinder. Actually, lead compounds are deposited in the combustion chamber and some find their way into the lubricating oil. The products of combustion of tetraethyllead fluid are also known to be corrosive. Since deposition and corrosive tendencies are undesirable, the quantity of tetraethyllead in aviation gasoline is limited by specification commensurate with economic considerations.

X1.2.8 Dyes—The law provides that all fuels containing tetraethyllead must be dyed to denote the presence of the poisonous
component. Colors are also used in aviation fuels to differentiate between grades. Service experience has indicated that only certain dyes and only certain amounts of dye can be tolerated without manifestation of induction system deposition. The names of the approved dyes are specified as well as the maximum quantity of each permissible in each grade.

XII.3 Fuel Metering and Aircraft Range

XII.3.1 Density—Density is a property of a fluid and is of significance in metering flow and in mass-volume relationships for most commercial transactions. It is particularly useful in empirical assessments of heating value when used with other parameters such as aniline point or distillation.

XII.3.2 Net Heat of Combustion—The net heat of combustion provides a knowledge of the amount of energy obtainable from a given fuel for the performance of useful work, in this instance, power. Aircraft design and operation are dependent upon the availability of a certain predetermined minimum amount of energy as heat. Consequently, a reduction in heat energy below this minimum is accompanied by an increase in fuel consumption with corresponding loss of range. Therefore, a minimum net heat of combustion requirement is incorporated in the specification. The determination of net heat of combustion is time consuming and difficult to conduct accurately. This led to the development and use of the aniline point and density relationship to estimate the heat of combustion of the fuel. This relationship is used along with the sulfur content of the fuel to obtain the net heat of combustion for the purposes of this specification. An alternative calculation, Test Method D 3338, is based on correlations of aromatics content, density, volatility, and sulfur content. This test method may be preferred at refineries where all these values are normally obtained and the necessity to obtain the aniline point is avoided. The direct measurement method is normally used only as a reference method in cases of dispute.

XII.3.3 No great variation in density or heat of combustion occurs in modern aviation gasolines, since they depend on hydrocarbon composition that is already closely controlled by other specification properties.

XII.4 Carburetion and Fuel Vaporization

XII.4.1 In many spark-ignition aviation engines, the gasoline is metered in liquid form through the carburetor where it is mixed with air and vaporized before entering the supercharger from which the fuel-air mixture enters the cylinder of the engine. In other types of engines, the fuel may be metered directly into the supercharger, the cylinder, or the combustor. The volatility, the tendency to evaporate or change from a liquid to a gaseous state, is an extremely important characteristic of aviation fuel.

XII.4.2 Gasolines that vaporize too readily may boil in fuel lines or carburetors, particularly as altitude increases, and cause vapor lock with resultant stoppage of fuel flow to the engine. Conversely, fuels that do not completely vaporize may cause engine malfunctioning of other sorts. Therefore, a proper balance of the volatility of the various hydrocarbon components is essential to satisfactory performance of the finished fuel.

XII.4.3 Vapor Pressure—The vapor pressure of an aviation gasoline is the measure of the tendency of the more volatile components to evaporate. Experience has shown that fuels having a Reid vapor pressure no higher than 49 kPa will be free of vapor-locking tendencies under most conditions of aircraft usage. A research report is available.\(^\text{5}\)

XII.4.4 Distillation—The relative proportions of all the hydrocarbon components of a gasoline are measured in terms of volatility by the range of distillation temperatures. The method is empirical and useful in comparing fuels, but is not intended to separate or identify quantitatively the individual hydrocarbons present in the fuel.

XII.4.4.1 A maximum value is set on the 10% evaporated point to ensure ease of starting and a reasonable degree of flexibility during the warm-up period. To guard against too high a volatility that might lead to carburetor icing or vapor lock, or both, (also protected against by the vapor pressure test) a minimum value is set for the sum of the 10% and 50% evaporated points.

XII.4.4.2 A maximum value is specified for the 50% evaporated temperature to ensure average volatility sufficient to permit adequate evaporation of the fuel in the engine induction system. Insufficient evaporation may lead to loss of power.

XII.4.4.3 A maximum temperature is prescribed for the 90% evaporated point to prevent too much liquid fuel being delivered to the cylinders, resulting in power loss, and to prevent poor distribution to the various cylinders. Such a condition might lead to excessive leanness in some cylinders with consequent engine roughness, perhaps accompanied by knocking and damage to the engine. Lowered fuel economy and excessive dilution of the lubricating oil may result from too high a 90% evaporated point.

XII.4.4.4 A minimum value is stipulated for the 40% evaporated temperature in an effort to control, indirectly, specific gravity and, consequently, carburetor metering characteristics.

XII.4.4.5 A maximum is placed on the final boiling point (end point) which, together with the maximum prescribed for the 90% evaporated point, is used to prevent incorporation of excessively high boiling components in the fuel that may lead to maldistribution, spark plug fouling, power loss, lowered fuel economy, and lubricating oil dilution.

XII.4.4.6 The stipulation of a minimum recovery and a maximum loss in this specification in conjunction with the vapor pressure requirement is intended to protect against excessive losses by evaporation in storage, handling, and in the aircraft tank. It is also a check on the distillation test technique.

XII.4.4.7 A maximum value is specified for the distillation residue to prevent the inclusion of undesirable high-boiling components essentially impossible to burn in the combustion chamber, the presence of which may reflect the degree of care with

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\(^5\) Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR: D02-1146.
which the product is refined or handled. The amount of residue along with the end point temperature can be used as an indication of contamination with high-boiling materials.

X1.5 Corrosion of Fuel System and Engine Parts

X1.5.1 Copper Strip—The requirement that gasoline must pass the copper strip corrosion test provides assurance that the product will not corrode the metal parts of fuel systems.

X1.5.2 Sulfur—Total sulfur content of aviation fuels is significant because the products of combustion of sulfur can cause corrosive wear of engine parts.

X1.6 Fluidity at Low Temperatures

X1.6.1 A freezing point requirement is specified to preclude solidification of any hydrocarbon components at extremely low temperatures with consequent interference with fuel flow to the engine.

X1.6.2 Fuel System Icing Inhibitor—Isopropyl alcohol (IPA), approved in 6.3.2.1, and diethylene glycol monomethyl ether (Di-EGME), approved in 6.3.2.2, shall be in accordance with the requirements shown in Specification D 4171.

X1.7 Fuel Cleanliness, Handling and Storage Stability

X1.7.1 Existent Gum—Gum is a non-volatile residue left by evaporation of fuel. The amount of gum present is an indication of the condition of the fuel at the time of test only. Large quantities of gum are indicative of contamination of fuel by higher boiling oils or particulate matter and generally reflect poor fuel handling practices.

X1.7.2 Potential Gum—Fuel must be usable after storage for varying periods under a variety of climatic conditions. The potential gum test, which is an accelerated oxidation method, is used to estimate fuel stability in storage and the effectiveness of oxidation inhibitors. If the fuel is to be stored under relatively mild conditions for short periods, an oxidation period of 5 h is generally considered sufficient to indicate if the desired stability has been obtained, whereas a 16-h period is desirable to provide stability assurance for long periods and severe conditions, such as storage in tropical climates.

X1.7.3 Visible Lead Precipitate—The formation of a lead precipitate during the aging period of the potential gum test under the accelerated oxidation conditions used in this determination indicates a potential instability. Since even small amounts of insoluble material may foul the induction system and plug filters, it is necessary to place a limit on the amount of precipitate formed in this determination.

X1.7.4 Permissible Oxidation Inhibitors and Oxidation Inhibitor Content—Antioxidants are used to prevent the formation of gum in fuel during storage. The efficacy of a given inhibitor determined by the apparent oxidation stability of a fuel does not completely establish its suitability for use in an aircraft engine. Oxidation inhibitors have been found to contribute to excessive induction system deposits; therefore, their acceptability for use must ultimately be determined in the full-scale aircraft engine.

X1.7.4.1 The chemical names of approved inhibitors and the maximum quantities permitted are shown in this specification.

X1.7.5 Water Reaction—The water reaction method provides a means of determining the presence of materials readily extractable by water or having a tendency to absorb water. When the fuel consists essentially of hydrocarbon components, there is no measurable change in the volume of the water layer.

X1.7.6 Electrical Conductivity—The generation of static electricity can create problems in the handling of aviation gasolines. Addition of a conductivity modifier may be used as an additional precaution to reduce the amount of static electrical charge present during fuel handling. See Guide D 4805 for more information.

X1.7.7 Microbial Contamination—Uncontrolled microbial contamination in fuel systems may cause or contribute to a variety of problems including corrosion, odor, filter plugging, decreased stability, and deterioration of fuel/water separation characteristics. In addition to system component damage, off-specification fuel can result.

X1.7.8 Guide D 6496 provides personnel with limited microbiological background and an understanding of the symptoms, occurrence, and consequences of chronic microbial contamination. The guide also suggests means for detection and control. Biocides used in aviation fuels must follow engine and airframe manufacturer’s approval guidelines.

X1.8 Miscellaneous Tests

X1.8.1 Aromatics Content—Low boiling aromatics, which are common constituents of aviation gasolines, are known to affect customers to a greater extent than other components in aviation gasoline. Although Specification D 910 does not include an explicit maximum aromatic limit, other specification limits effectively restrict the aromatic content of aviation gasolines. Benzene is virtually excluded by the maximum freezing point of −58°C, while other aromatics are limited by the minimum heating value and the maximum distillation end point. Thus, the heating value limits toluene to about 24%. Xylenes have a slightly higher heating value and, therefore, would permit somewhat higher aromatic concentrations; however, their boiling points (above 138°C) limit their inclusion at levels not higher than 10%. Total aromatic levels above 25% in aviation gasoline are, therefore, extremely unlikely.
X1.9 General

X1.9.1 Further detailed information on the significance of all test methods relevant to aviation gasoline is provided in Manual MNL 1.9

SUMMARY OF CHANGES

Subcommittee D02.10 has identified the location of selected changes to this standard since the last issue (D 910-06) that may impact the use of this standard. (Approved Dec. 1, 2007.)

(1) Revised Footnote C in Table 1.

(2) Revised X1.2.5.

(3) Revised list in 6.3.4.

(4) Added 9.1.1.

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Standard Specification for Automotive Spark-Ignition Engine Fuel

This standard is issued under the fixed designation D 4814; the number immediately following the designation indicates the year of
original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A
superscript epsilon (e) indicates editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This specification covers the establishment of requirements of automotive fuels for ground vehicles equipped with
spark-ignition engines.

1.2 This specification describes various characteristics of automotive fuels for use over a wide range of operating conditions. It provides for a variation of the volatility and water tolerance of automotive fuel in accordance with seasonal climatic changes at the locality where the fuel is used. For the period May 1 through Sept. 15, the maximum vapor pressure limits issued by the U.S. Environmental Protection Agency (EPA) are specified for each geographical area except Alaska and Hawaii. Variation of the antiknock index with seasonal climatic changes and altitude is discussed in Appendix X1.

1.3 The spark-ignition engine fuels covered in this specification are gasoline and its blends with oxygenates, such as alcohols and ethers. This specification does not apply to fuels that contain an oxygenate as the primary component, such as Fuel Methanol (M85). The concentrations and types of oxygenates are not specifically limited in this specification. However, depending on oxygenate type, as oxygenate content increases above some threshold level, the likelihood for vehicle problems also increases. The composition of both unleaded and leaded fuel is limited by economic, legal, and technical consideration, but their properties, including volatility, are defined by this specification. In addition, the composition of unleaded fuel is subject to the rules, regulations, and Clean Air Act waivers of the U.S. Environmental Protection Agency (EPA). With regard to fuel properties, including volatility, this specification can be more or less restrictive than the EPA rules, regulations, and waivers. Refer to Appendix X3 for discussions of EPA rules relating to fuel volatility, lead and phosphorous contents, deposit control additive certification, and use of oxygenates in blends with unleaded gasoline. Contact the EPA for the latest versions of the rules and additional requirements.

1.4 This specification does not address the emission characteristics of reformulated spark-ignition engine fuel. Reformulated spark-ignition engine fuel is required in some areas to lower emissions from automotive vehicles, and its characteristics are described in the research report on reformulated spark-ignition engine fuel.2 However, in addition to the legal requirements found in this research report, reformulated spark-ignition engine fuel should meet the performance requirements found in this specification.

1.5 This specification represents a description of automotive fuel as of the date of publication. The specification is under continuous review, which can result in revisions based on changes in fuel, automotive requirements, or test methods, or a combination thereof. All users of this specification, therefore, should refer to the latest edition.

Notes:
1. If there is any doubt as to the latest edition of Specification D 4814, contact ASTM International Headquarters.
2. Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report R&D02-1347.

*A Summary of Changes section appears at the end of this standard.
TABLE 1 Vapor Pressure and Distillation Class Requirements

<table>
<thead>
<tr>
<th>Vapor Pressure, kPa</th>
<th>Distillation Temperature, °C [T], at % Evaporated, max</th>
<th>Distillation Residue, volume %, max</th>
<th>Devolatibility Index, % Derived</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor Pressure, max</td>
<td>10 volume %, max</td>
<td>20 volume %, max</td>
<td>90 volume %, max</td>
</tr>
<tr>
<td>AA</td>
<td>54 (7.8)</td>
<td>70 (105)</td>
<td>77 (170)</td>
</tr>
<tr>
<td>A</td>
<td>62 (9.0)</td>
<td>70 (105)</td>
<td>77 (170)</td>
</tr>
<tr>
<td>B</td>
<td>88 (12.0)</td>
<td>88 (130)</td>
<td>95 (200)</td>
</tr>
<tr>
<td>C</td>
<td>76 (11.0)</td>
<td>60 (90)</td>
<td>77 (170)</td>
</tr>
<tr>
<td>D</td>
<td>54 (8.0)</td>
<td>50 (75)</td>
<td>77 (170)</td>
</tr>
<tr>
<td>E</td>
<td>103 (15.0)</td>
<td>50 (75)</td>
<td>77 (170)</td>
</tr>
</tbody>
</table>

a See 1.7 for determining conformance with specification limits in this table. When using this table to determine conformance of gasoline volatility, the reader is advised to review other possible requirements for example, EPA Substantially Similar rule, California Air Resources Board (CARB), Clean Burning Gasoline (CBG), other state or local and pipeline specifications.

b Consult EPA for approved test methods for compliance with EPA vapor pressure regulations.

c At 101.3 kPa pressure (760 mm Hg).

d Devolatibility Index [D] = 1.0 × (T90 − 30) + 0.5 × (T60 − 50) + 1.3 × (T30 − 10) × Ethanol Volume %, where T90 = distillation temperature, °C, at 10 % evaporated, T60 = distillation temperature, °C, at 60 % evaporated, T30 = distillation temperature, °C, at 30 % evaporated, and 1.3 is the coefficient for the volume %, ethanol present when the distillation results are determined in degrees Celsius and 2.4 is the coefficient when distillation results are determined in degrees Fahrenheit.

e The DI specification limits are applicable at the refinery or import facility as defined by 40 CFR. Part 80.2 and are not subject to correction for precision of the test method.

f If the DI is an index and has no units, the standard temperature conversion from U.S. customary to SI units is not appropriate. The following equation is to be used to make the conversion: 1DI,US = 1DI,SI × 1.8.

Gasolines that may be blended with 1 to 10 volume percent ethanol or all other gasolines whose disposition with ethanol blending is not known shall meet a minimum 50 % evaporated distillation temperature of 77°C (171°F) or prior to blending with ethanol. Gasolines contain 1 to 10 volume percent ethanol shall meet a minimum 50 % evaporated distillation temperature of 66°C (150°F) after blending.

Gasolines known from the origin to result that will not be blended with ethanol may meet a minimum 90 % evaporated distillation temperature of 66°C (150°F) for volatility classes D and E only. Gasolines meeting these limits are not suitable for blending with ethanol.

Decimal point is specified. For a specified limit expressed as an integer, the right-most digit is non-zero, the right-most digit is significant without a decimal point being specified. This convention applies to specified limits in Tables 1, 3, and Table X8.1, and it will not be observed in the remainder of this specification.

1.8 The values stated in SI units are the standard, except when other units are specified by federal regulations. Values given in parentheses are provided for information only.

NOTE 2—Many of the values shown in Table 1 were originally developed using U.S. customary units and were subsequently converted to SI values. As a result, conversion of the SI values will sometimes differ slightly from the U.S. customary values shown because of rounding off. In some cases, federal regulations specify non-SI units.

1.9 The following safety hazard caveat pertains only to the test method portion, Annex A1, of this specification. This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:3

D 86 Test Method for Distillation of Petroleum Products at Atmospheric Pressure

D 130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test

D 287 Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)

D 381 Test Method for Gum Content in Fuels by Jet Evaporation

D 439 Specification for Automotive Gasoline4

D 525 Test Method for Oxidation Stability of Gasoline (Inhibition Period Method)

D 1266 Test Method for Sulfur in Petroleum Products (Lamp Method)

D 1298 Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method

D 2622 Test Method for Sulphur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry

D 2699 Test Method for Research Octane Number of Spark-Ignition Engine Fuel

D 2700 Test Method for Motor Octane Number of Spark-Ignition Engine Fuel

D 2885 Test Method for Determination of Octane Number of Spark-Ignition Engine Fuels by On-Line Direct Comparison Technique

D 3120 Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry

D 3231 Test Method for Phosphorus in Gasoline

D 3237 Test Method for Lead in Gasoline by Atomic Absorption Spectroscopy

D 3341 Test Method for Lead in Gasoline—Iodine Monochloride Method

D 4052 Test Method for Density and Relative Density of Liquids by Digital Density Meter

D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products

D 4177 Practice for Automatic Sampling of Petroleum and Petroleum Products

3 For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard’s Document Summary page on the ASTM website.

4 Withdrawn.
D 4814 – 09

D 306 Practice for Aviation Fuel Sample Containers for Tests Affected by Trace Contamination

D 4815 Test Method for Determination of MTBE, ETBE, TAME, DIPE, tertiary-Amyl Alcohol and C7 to C4 Alcohols in Gasoline by Gas Chromatography

D 4953 Test Method for Vapor Pressure of Gasoline and Gasoline-Oxygenate Blends (Dry Method)

D 5059 Test Methods for Lead in Gasoline by X-Ray Spectroscopy

D 5188 Test Method for Vapor-Liquid Ratio Temperature Determination of Fuels (Evacuated Chamber Method)

D 5190 Test Method for Vapor Pressure of Petroleum Products (Automatic Method)

D 5191 Test Method for Vapor Pressure of Petroleum Products (Mini Method)

D 5453 Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence

D 5482 Test Method for Vapor Pressure of Petroleum Products (Mini Method—Atmospheric)

D 5500 Test Method for Vehicle Evaluation of Unleaded Automotive Spark-Ignition Engine Fuel for Intake Valve Deposit Formation


D 5599 Test Method for Determination of Oxygenates in Gasoline by Gas Chromatography and Oxygen Selective Flame Ionization Detection

D 5842 Practice for Sampling and Handling of Fuels for Volatility Measurement

D 5845 Test Method for Determination of MTBE, ETBE, TAME, DIPE, Methanol, Ethanol and Isopropyl Alcohol in Gasoline by Infrared Spectroscopy

D 5854 Practice for Mixing and Handling of Liquid Samples of Petroleum and Petroleum Products

D 6469 Guide for Microbial Contamination in Fuels and Fuel Systems

D 6920 Test Method for Total Sulfur in Naphthas, Distillates, Reformulated Gasolines, Diesels, Biodiesels, and Motor Fuels by Oxidative Combustion and Electrochemical Detection

D 7039 Test Method for Sulfur in Gasoline and Diesel Fuel by Monochromatic Wavelength Dispersive X-ray Fluorescence Spectrometry

E 29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

2.2 Government Standard:

CFR 40 Code of Federal Regulations

2.3 Other Standard:

CCR Title 17, §60100–160114 California Code of Regulations

3. Terminology

3.1 Definitions:

3.1.1 antiknock index, n—the arithmetic average of the Research octane number (RON) and Motor octane number (MON), that is, (RON + MON)/2.

3.1.2 gasoline, n—a volatile mixture of liquid hydrocarbons, generally containing small amounts of additives, suitable for use as a fuel in spark-ignition, internal combustion engines.

3.1.3 gasoline-alcohol blend, n—a fuel consisting primarily of gasoline along with a substantial amount (more than 0.35 mass % oxygen, or more than 0.15 mass % oxygen if methanol is the only oxygenate) of one or more alcohols.

3.1.4 gasoline-ether blend, n—a fuel consisting primarily of gasoline along with a substantial amount (more than 0.35 mass % oxygen) of one or more ethers.

3.1.5 gasoline-oxygenate blend, n—a fuel consisting primarily of gasoline along with a substantial amount (more than 0.35 mass % oxygen, or more than 0.15 mass % oxygen if methanol is the only oxygenate) of one or more oxygenates.

3.1.6 oxygenate, n—an oxygen-containing, ashless, organic compound, such as an alcohol or ether, which can be used as a fuel or fuel supplement.

3.1.7 refinery, n—a plant at which gasoline or diesel fuel is produced.

3.1.7.1 Discussion—This definition is from CFR 40 Part 80.2. In the federal definition, a plant not only covers the conventional refinery, but also covers oxygenate blending and other facilities where gasoline is produced.

3.2 Applicability—To determine when a fuel contains a substantial amount of an oxygenate, a gasoline-oxygenate blend is defined as a fuel that contains more than 0.35 mass % oxygen, or more than 0.15 mass % oxygen if methanol is the only oxygenate. The definitions in this section do not apply to fuels that contain an oxygenate as the primary component; for example, fuel methanol (M85).

Note 3—The criteria in 3.2 were selected with consideration given to current oxygenate levels in the marketplace, state labeling practices, and consistency with federal legislation and regulations.

Note 4—Refer to Test Method D 4815 to calculate the mass oxygen content of a fuel using oxygenate concentration in mass %. Refer to Appendix X4 to calculate mass oxygen content of a fuel using oxygenate concentration in volume %.

4. Ordering Information

4.1 The purchasing agency shall:

4.1.1 State the antiknock index as agreed upon with the seller,

4.1.2 Indicate the season and locality in which the fuel is to be used,

4.1.3 Indicate the level required (Table 2), and

4.1.4 State the concentration and types of oxygenates present as agreed upon with the seller.

5. Performance Requirements

5.1 Some requirements and test methods applicable to automotive spark-ignition engine fuel depend on whether the fuel is a gasoline, or a gasoline-oxygenate blend. Test Methods D 4815 and D 5599, gas chromatographic test methods, are the recommended procedures to detect the types and amounts of oxygenates. Once the type of fuel is known, the appropriate
requirements and test methods can be identified by reference to

Table 1, Table 3, and Section 7.

5.2 Volatility of fuels is varied for seasonal climatic changes and conformance to U.S. EPA volatility regulations by providing six vapor pressure/distillation classes and six vapor lock protection classes for fuel. Volatility of fuel is specified by an alphanumeric designation that uses a letter from Table 1 and a number from Table 3.

5.2.1 The seasonal and geographic distribution of the combined vapor pressure/distillation-vapor lock classes is shown in Table 4. Tables 5-7 show the federal ozone nonattainment areas at several vapor lock protection levels that require reduced vapor pressure in the summertime. Tables 8-11 show at several vapor lock protection levels the areas that require federal reformulated spark-ignition engine fuel in the summertime.

Table 12 shows the areas with restrictive local vapor pressure limits that have been approved under the EPA state implementation plan (SIP).

5.2.2 The EPA vapor pressure regulations can cause the distillation of the fuel to be less volatile, which for some vehicles, results in a worse warm-up driveability performance.

5.2.3 Driveability Index (DI) is intended to provide control of distillation parameters and ethanol content that influence cold start and warm-up driveability. It is a function of the 10%, 50%, and 90% evaporated distillation temperatures measured by Test Method D 66 and the ethanol content measured by the test methods shown in 7.1.9.

5.2.4 Test Method D 5188 is the method for determining vaporliquid ratio temperatures by an evacuated chamber method for gasoline-oxygenate blends, as well as for gasoline. The methods for estimating temperature-V/L (see Appendix X2) are applicable for gasoline and gasoline-ethanol blends (1 to 10 volume %), but not for gasoline-oxygenate blends.

5.3 Anti-knock index (AKI) is very important to engine performance. The matching of engine octane requirement to fuel octane level (AKI) is critical to the durability and performance of engines; this cannot be accomplished with a single specified minimum level of anti-knock index. Appendix X1 includes a discussion of anti-knock indexes of fuels currently marketed and relates these levels to the octane needs of broad groups of engines and vehicles. Also discussed is the effect of altitude and weather on vehicle anti-knock requirements.

5.4 Additional fuel requirements are shown in Table 2.

5.5 The properties of gasoline-oxygenate blends can differ considerably from those of gasoline. Consequently, additional requirements are needed for gasoline-oxygenate blends. These requirements involve evaluation of compatibility with plastic and elastomeric materials in fuel systems, corrosion of metals, and especially in the case of gasoline-oxygenate blends, water tolerance. Requirements for metal corrosion (other than copper) and material compatibility are not given because test methods and appropriate limits are still under development. When these have been developed, they will be included in this specification.

5.6 Depending on oxygenate type and concentration in the blend, vehicle driveability with gasoline-oxygenate blends can differ significantly from that with gasoline having similar volatility characteristics.

5.7 Water Tolerance:

5.7.1 The term water tolerance is used to indicate the ability of a gasoline-oxygenate blend to dissolve water without phase separation. This may not be a problem with gasoline-oxygenate blends, but it is of primary concern for alcohol-containing blends, as blends of gasoline with low-molecular weight alcohols generally will dissolve about 0.1 to 0.7 mass % of water under normal conditions, depending on the nature and amount of the alcohol(s) used, the specific hydrocarbons present, and the temperature of the blend. Additional information on water tolerance is provided in Appendix X8.
TABLE 4 Schedule of Seasonal and Geographical Volatility Classes

NOTE 1—This schedule, subject to agreement between purchaser and seller, denotes the volatility properties of the fuel at the time and place of bulk delivery to the fuel dispensing facilities for the end user. For Sept. 16 through April 30 (the time period not covered by EPA Phase II vapor pressure requirements), volatility properties for the previous month or the current month are acceptable for the end user from the 1st through the 15th day of the month. From the 16th day through the end of the month, volatility properties of the fuel delivered to the end user shall meet the requirements of the specified class. To ensure compliance with EPA Phase II vapor pressure requirements, vapor pressure for finished gasoline tankerage at refineries, importers, pipelines, and terminals during May and for the entire distribution system, including retail stations, from June 1 to Sept. 15 shall meet only the current month’s class. Shipments should anticipate this schedule.

NOTE 2—Where alternative classes are listed, either class or intermediate classes are acceptable; the option shall be exercised by the seller.

NOTE 3—See Appendix X2 of Report Research: D62-1347 for detailed description of areas. Contact EPA for the latest information on areas requiring reformulated fuel.

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<td>D4</td>
<td>D4</td>
<td>D4/4</td>
<td>C3/3-3</td>
<td>A3(-C3)</td>
<td>A3(-C)</td>
<td>A2D/2</td>
<td>A2D</td>
<td>A2D/2</td>
<td>C3-3</td>
<td>C3/3-3</td>
<td>D4</td>
</tr>
<tr>
<td>Tennessee</td>
<td>D4</td>
<td>D4</td>
<td>D4</td>
<td>D4/4</td>
<td>C3/3-3</td>
<td>A3(-C3)</td>
<td>A3(-C)</td>
<td>A2D/2</td>
<td>A2D</td>
<td>A2D/2</td>
<td>C3-3</td>
<td>C3/3-3</td>
<td>D4</td>
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<tr>
<td>Texas</td>
<td>D4</td>
<td>D4</td>
<td>D4</td>
<td>D4/4</td>
<td>C3/3-3</td>
<td>A3(-C3)</td>
<td>A3(-C)</td>
<td>A2D/2</td>
<td>A2D</td>
<td>A2D/2</td>
<td>C3-3</td>
<td>C3/3-3</td>
<td>D4</td>
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TABLE 4

<table>
<thead>
<tr>
<th>State</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>E 90° Longitude</td>
<td>D 4</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
</tr>
<tr>
<td>W 90° Longitude</td>
<td>D 4</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
</tr>
<tr>
<td>Utah</td>
<td>E 5</td>
<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
</tr>
<tr>
<td>Vermont</td>
<td>E 5</td>
<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
</tr>
<tr>
<td>Washington</td>
<td>E 5</td>
<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
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<td>D 4</td>
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<td>A 3D-3</td>
</tr>
<tr>
<td>E 120° Longitude</td>
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<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
</tr>
<tr>
<td>W 120° Longitude</td>
<td>E 5</td>
<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
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<td>West Virginia</td>
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<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
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<tr>
<td>Wisconsin</td>
<td>E 5</td>
<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
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<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
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<td>Wyoming</td>
<td>E 5</td>
<td>E 5</td>
<td>D 4</td>
<td>A 3</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
<td>D 4</td>
<td>C 3D-3</td>
<td>A 3D-3</td>
</tr>
</tbody>
</table>

* For the period May 1 through September 15, the specified vapor pressure classes comply with 1992 U.S. EPA Phase II volatility regulations. Reformulated spark-ignition engine fuel blended to meet the requirements of the EPA Complex Model shall also meet the Phase II volatility regulations. EPA regulations (under the Phase II regulations) allow 1.0 psi higher vapor pressure for gasoline ethanol blends containing 10% ethanol for the same period, except for fuels blended to maintain the Complex Model regulations. See Appendix X for additional federal volatility regulations.

Values in parentheses are permitted for retail stations and other end uses.

D See Table 5 for specific area requirements.
D See Table 6 for specific area requirements.
D See Table 13 for specific area requirements.
D See Table 13 for specific area requirements.

* Details of State Climatological Division by CAIR air basin and county as indicated.

* Descriptions of the California Air Basins are found in the California Code of Regulations.

* California, North Coast—CARB North Coast, Lake County, San Francisco Bay Area, and North Central Coast Air Basins (Alameda, Contra Costa, Del Norte, Humboldt, Lake, Marin, Mendocino, Monterey, Napa, San Benito, San Francisco, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, and Trinity Counties and part of Solano County).


* California, South Coast—CARB South Central Coast, San Diego, and South Coast Air Basins (Los Angeles, Orange, San Diego, San Luis Obispo, Santa Barbara, and Ventura Counties, and parts of Riverside and San Bernardino Counties).

TABLE 5 Ozone Nonattainment Areas Requiring Volatility Class AA-3

Norm—See 40 CFR Part 81.300 for description of the geographic boundary for each area.

Alabama—Jefferson and Shelby counties

Florida—Miami-Dade, Broward, Hillsborough, Palm Beach, and Pinellas counties

Georgia—Chatham, Clay, Cobb, Coweta, Dacula, Douglas, Fayette, Forsyth, Fulton, Gwinnett, Henry, Paulding, and Rockdale counties


Missouri—Franklin, Jefferson, Saint Charles, Saint Louis, and Stoddard counties, and the city of St. Louis

North Carolina—Davidson, Davie (part), Durham, Forsyth, Gaston, Granville (part), Guilford, Mockebuck, and Wake counties

North Dakota—Cass, McIntosh, and Pembina (part) counties

Oregon—Clackamas (part), Marion (part), Multnomah (part), Polk (part), and Washington (part) counties

Tennessee—Davidson, Rutherford, Shelby, Sumner, Williamson, and Wilson counties

Texas—Hardin, Jefferson, Orange, and Victoria counties

Virginia—Smyth County (part)

* See Table 12 for local vapor pressure limits.

5.8 Deposit control additives are added to fuel to help keep carburetors, fuel injectors, and intake valves clean. Deposit control additives are required to be certified by the EPA as summarized in X3.5. Each additive is certified for use at a lowest additive concentration (LAC), which is the lowest level certified to be effective in preventing deposit formation. All parties who blend deposit control additives into fuel must
TABLE 7 Ozone Nonattainment Areas Requiring Volatility Class AA-1

<table>
<thead>
<tr>
<th>Area</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arizona</td>
<td>Maricopa County</td>
</tr>
<tr>
<td>California</td>
<td>Imperial and Kern (part) counties</td>
</tr>
<tr>
<td>Nevada</td>
<td>El Paso County</td>
</tr>
</tbody>
</table>

*See Table 12 for local vapor pressure limits.

TABLE 8 Federal RFG Areas Requiring Volatility Class A-3

<table>
<thead>
<tr>
<th>Area</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connecticut</td>
<td>All counties</td>
</tr>
<tr>
<td>Delaware</td>
<td>All counties</td>
</tr>
<tr>
<td>Illinois</td>
<td>Cook, Du Page, Grundy (part), Kane, Kendall (part), Lake, McHenry, and Will counties</td>
</tr>
<tr>
<td>Indiana</td>
<td>Lake and Porter counties</td>
</tr>
<tr>
<td>Kentucky</td>
<td>Boone, Bullitt (part), Campbell, Jefferson, Kenton, and Oldham (part) counties</td>
</tr>
<tr>
<td>Maryland</td>
<td>Caci County</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>All counties</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>Hillsborough, Merrimack, Rockingham, and Stafford counties</td>
</tr>
<tr>
<td>New Jersey</td>
<td>All counties</td>
</tr>
<tr>
<td>New York</td>
<td>Bronx, Dutchess, Essex (part), Kings, Nassau, New York, Orange, Putnam, Queens, Richmond, Rockland, Suffolk, and Westchester counties</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>Berks, Chester, Delaware, Montgomery, and Philadelphia counties</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>All counties</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>Kaukauna, Manitowoc, Ozaukee, Racine, Washington, and Waukesha counties</td>
</tr>
</tbody>
</table>

*See Table 12 for local vapor pressure limits.

TABLE 9 Federal RFG Areas Requiring Volatility Class AA-3

<table>
<thead>
<tr>
<th>Area</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>District of Columbia</td>
<td>All counties</td>
</tr>
<tr>
<td>Maryland</td>
<td>Anne Arundel, Baltimore, Calvert, Carroll, Charles, Frederick, Harford, Howard, Kent, Montgomery, Prince George's, and Queen Anne's counties</td>
</tr>
<tr>
<td>Texas</td>
<td>Atascosa, Chambers, Collin, Dallas, Denton, Fort Bend, Galveston, Harris, Liberty, Montgomery, Tarrant, and Waller counties</td>
</tr>
<tr>
<td>Virginia</td>
<td>Arlington, Charles City, Chesterfield, Fairfax, Hanover, Henrico, James City, Loudoun, Prince William, Stafford, and York counties and independent cities of Alexandria, Chesapeake, Colonial Heights, Fairfax, Falls Church, Hampton, Hopewell, Manassas, Manassas Park, Newport News, Norfolk, Poquoson, Portsmouth, Richmond, Suffolk, Virginia Beach, and Williamsburg</td>
</tr>
</tbody>
</table>

TABLE 10 Federal RFG Areas Requiring Volatility Class AA-2

<table>
<thead>
<tr>
<th>Area</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>El Dorado (part), Los Angeles, Orange, Placer (part), Riverside (part), Sacramento, San Bernardino (part), San Diego, Solano (part), Sutter (part), Ventura, and Yolo counties</td>
</tr>
<tr>
<td>Texas</td>
<td>Bastrop, Chambers, Collin, Dallas, Denton, Fort Bend, Galveston, Harris, Liberty, Montgomery, Tarrant, and Waller counties</td>
</tr>
</tbody>
</table>

*See Table 12 for local vapor pressure limits.

TABLE 11 Federal RFG Area Requiring Volatility Class AA-1

<table>
<thead>
<tr>
<th>Area</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>Los Angeles (part), Riverside (part), and San Bernardino (part) counties</td>
</tr>
</tbody>
</table>

*See Table 12 for local vapor pressure limits.

Oxygenate blends can produce changes in appearance that are not reversed on reworking.

The finished fuel shall also be free of any adulterant or contaminant that may render the fuel unacceptable for its commonly used applications.

7. Test Methods

7.1 The requirements of this specification shall be determined in accordance with the methods listed below. Refer to the listed test methods to determine applicability or required modifications for use with gasoline-oxygenate blends.

7.1.1 Distillation—Test Method D 86

7.1.2 Vapor-Liquid Ratio—Test Method D 5188 is an evacuated chamber method for determining temperatures for vapor-liquid ratios between 8 to 1 and 75 to 1. For this specification, it is conducted at a ratio of 20 to 1. It may be used for gasoline and gasoline-oxygenate blends.

7.1.3 Vapor Pressure—Test Methods D 4953, D 5190, D 5191, or D 5462

7.1.4 Corrosion, for Copper—Test Method D 130, 3 h at 50°C (122°F)

7.1.5 Solvent-Washed Gum Content—Test Method D 381, air jet apparatus

7.1.6 Sulfur—Test Methods D 1266, D 2622, D 3120, D 5453, D 6920, or D 7039. With Test Method D 3120, fuels with sulfur content greater than 100 ppm (0.010 mass %) must be diluted with isooctane. The dilution of the sample may result in a loss of precision. Test Method D 3120 cannot be used when the lead concentration is greater than 0.4 g/l (1.4 g/U.S. gal).

7.1.7 Lead—Test Methods D 3341 or D 5059 (Test Methods A or B). For lead levels below 0.03 g/l (0.1 g/U.S. gal), use Test Methods D 3237 or D 5059 (Test Method C)

7.1.8 Oxidation Stability—Test Method D 525

7.1.9 Oxygenate Detection—Test Methods D 4815, D 5590, or D 5845. These test methods are designed for the quantitative determination of methyl tert-butyl ether (MTBE), ethyl tert-butyl ether (ETBE), tert-amyl methyl ether (TAME), diisopropyl ether (DIPE), methyl alcohol, ethyl alcohol, and tert-butyl alcohol.
TABLE 12 Federally Approved State Implementation Plan Areas
Suggesting More Restrictive Maximum Vapor Pressure Limits

<table>
<thead>
<tr>
<th>State</th>
<th>Counties</th>
<th>Maximum Vapor Pressure Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>Jefferson and Shelby counties</td>
<td>62.6 kPa (7.0 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Arizona</td>
<td>Maricopa County, Pinal (part), and Yavapai (part)</td>
<td>48.2 kPa (7.0 psi) max May 31 - Sept. 30, 62.6 kPa (9.0 psi) max Oct. 1 - Mar. 31</td>
</tr>
<tr>
<td>California</td>
<td>38.51 kPa (7.0 psi) max April 1, May 1 - June 1 - Sept. 30 or Oct. 1 depending on air basin</td>
<td></td>
</tr>
<tr>
<td>Georgia</td>
<td>Bank, Barrow, Bartow, Butte, Chattooga, Cherokee, Clay, Coweta, Coweta, Dade, Douglas, Fayette, Floyd, Forsyth, Fulton, Gordon, Gwinnett, Hall, Haralson, Heard, Henry, Jackson, Jasper, Jones, Lumpkin, Madison, Marion, Monroe, Morgan, Newton, Oconee, Paulding, Pickens, Pike, Polk, Putnam, Rockdale, Spalding, Troup, Upson, and Walton counties</td>
<td>48.2 kPa (7.0 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Illinois</td>
<td>Madison, Monroe, and St. Clair Counties area</td>
<td>49.6 kPa (7.2 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Indiana</td>
<td>Clark and Floyd counties area</td>
<td>53.8 kPa (7.8 psi) max June 1 to Oct. 1</td>
</tr>
<tr>
<td>Kansas</td>
<td>Johnson and Wyandotte counties</td>
<td>48.2 kPa (7.0 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Maine</td>
<td>Androscoggin, Penobscot, Knox, Lincoln, Sagadahoc, and York Counties</td>
<td>53.8 kPa (7.8 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Michigan</td>
<td>Lapeer, Livingston, Macomb, Monroe, Oakland, Saint Clair, Washtenaw, and Wayne counties</td>
<td>48.2 kPa (7.0 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Missouri</td>
<td>Clay, Jackson, and Platte counties</td>
<td>48.2 kPa (7.0 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Ohio</td>
<td>Butler, Clark, Clermont, Clinton, Greene, Hamilton, Miami, Montgomery, and Warren counties</td>
<td>53.8 kPa (7.8 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>Washington County, Rhode Island</td>
<td>53.8 kPa (7.8 psi) max June 1 - Sept. 10</td>
</tr>
<tr>
<td>Texas</td>
<td>El Paso County</td>
<td>49.2 kPa (7.0 psi) max June 1 to Oct. 1</td>
</tr>
</tbody>
</table>

8.3 The correct sample volume and appropriate container selection are important decisions that can impact test results. Refer to Practice D 4306 for aviation fuel container selection for tests sensitive to trace contamination. Refer to Practice D 5854 for procedures on container selection and sampling method and handling. For octane number determination, protection from light is important. Collect and store sample fuels in an opaque container, such as a dark brown glass bottle, metal can, or minimally reactive plastic container to minimize exposure to UV emissions from sources such as sunlight or fluorescent lamps.

8.4 For volatility determination of a sample, refer to Practice D 5842 for special precautions recommended for representative sample handling and sampling techniques.

9. Precision and Bias

9.1 The precision of each required test method for the properties specified is included in the standard applicable to each method, with the exception of Driveability Index. In many cases, the precision applicable to gasoline-oxygenate blends has not been established yet.

9.2 Precision and Bias of Driveability Index (DI):

9.2.1 The following statements apply to the precision and bias of DI, which is a derived quantity not addressed in any other standard.

9.2.2 The precision of DI is a function of the individual precision of the 10%, 50%, and 90% evaporated temperatures from Test Method D 86. The precisions of these percent evaporated temperatures vary with different apparatus (manual or automatic), for fuels of different volatilities (for example, above and below 65.5 kPa (9.5 psi) vapor pressure) and with different distillation curve shapes.

9.2.3 Repeatability—The difference between two successive DI determinations using Test Method D 86 results, where the two test results were obtained by one operator with the same apparatus under constant operating conditions on identical test material, would be in the run, in normal and correct operation of the test method, exceed 9°C (17°F) derived units in only one case in twenty.

9.2.4 The repeatability value was calculated using the precision data from Test Method D 86 and average distillation characteristics from the 1994 through 1998 ASTM Committee D02 Interlaboratory Crosscheck Program for Motor Gasoline and from the 1997 and 1998 ASTM Committee D02 Interlaboratory Crosscheck Program for Reformulated Gasoline.

9.2.5 Reproducibility—The difference between two single and independent DI determinations using Test Method D 86 results, where the two test results were obtained by different operators in different laboratories on identical test material, would be in the run, in normal and correct operation of the test method, exceed 27°C (48°F) derived units in only one case in twenty.

9.2.6 The reproducibility values were determined directly using the distillation data from each laboratory participating in cooperative programs to calculate DI. The data used to...
calculate DI were available from the 1994 through 1998 ASTM Committee D02 Interlaboratory Crosscheck Program for Motor Gasoline, the 1997 and 1998 ASTM Committee D02 Interlaboratory Crosscheck Program for Reformulated Gasoline, the AutoOil Air Quality Improvement Research Program, the AutoOil AAMA Gasoline Inspections Program, and the 1995 to 1996 CRC volatility program.

9.2.7 Bias—Since there is no acceptable reference material suitable for determining bias for DI, bias has not been determined.

10. Keywords

10.1 alcohol; antiknock index; automotive fuel; automotive gasoline; automotive spark-ignition engine fuel; copper strip corrosion; corrosion; distillation; driveability; Driveability Index; EPA regulations; ethanol; ether; fuel; gasoline; gasoline-alcohol blend; gasoline-ethanol blend; gasoline-ether blend; gasoline-oxygenate blend; induction period; lead; leaded fuel; methanol; MTBE; octane number; octane requirement; oxidation stability; oxygenate; oxygenate detection; phase separation; phosphorous; solvent-washed gum; sulfur; \( T_{\text{VM}} = 20 \); unleaded fuel; vapor-liquid ratio; vapor lock; vapor pressure; volatility; water tolerance

ANNEX

(Mandatory Information)

A1. TEST METHOD FOR CORROSIVENESS OF SILVER FROM PETROLEUM PRODUCTS BY SILVER STRIP TEST

A1.1 Scope

A1.1.1 This test method covers the determination of the corrosiveness of silver from a sample of automotive gasoline having a vapor pressure no greater than 124 kPa (18 psi) at 37.8°C (100°F).

A1.1.2 The values stated in SI units are to be regarded as the standard. The values in parentheses are for information only.

A1.1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use. For specific warning statements, see A1.6.1, and A1.7.

A1.2 Referred Documents

A1.2.1 ASTM Standards:

D 3241 Test Method for Thermal Oxidation Stability of Aviation Turbine Fuels (JFTOT Procedure)

D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products

D 4177 Practice for Automatic Sampling of Petroleum and Petroleum Products

E 1 Specification for ASTM Liquid-In-Glass Thermometers

A1.2.2 ASTM Annex:

Color Standard for Tube Deposit Rating

A1.3 Summary of Test Method

A1.3.1 A polished silver strip is immersed in a specific volume of the sample being tested and heated under conditions...
A1.5.3.2 Liquid Bath Used for Submerging Pressure Vessel(s)—The bath shall be deep enough to submerge one or more pressure vessels (see A1.5.1) completely during the test. As the bath medium, use water or any liquid that can be satisfactorily controlled to the sample test temperature. The bath shall be fitted with suitable supports to hold each pressure vessel in a vertical position when submersed.

A1.5.4 Temperature Sensing Device (TSD), capable of monitoring the desired test temperature in the bath to within an accuracy of ±1°C (2°F) or better. The ASTM 12C (12F) (see Specification E1) or IP 64C (64F) total immersion thermometers have been found suitable to use in the test. If used, no more than 10-mm (0.4-in.) of the mercury should extend above the surface of the bath at the test temperature.

A1.5.5 Polishing Vise, for holding the silver strip firmly without marring the edges while polishing. Any convenient type of holder (see Appendix X7) may be used provided that the strip is held tightly and that the surface of the strip being polished is supported above the surface of the holder.

A1.5.6 Viewing Test Tubes, flat glass test tubes, are convenient for protecting corroded silver strips for close inspection or storage (see Appendix X7 for the description of a flat-glass viewing tube). The viewing test tube shall be of such dimensions as to allow the introduction of a silver strip (see A1.6.3) and made of glass free of strie or similar defects.

A1.5.7 Forceps, with either stainless steel or polytetrafluoroethylene (PTFE) tips, for use in handling the silver strips, have been found suitable to use.

A1.5.8 Timing Device, electronic or manual, capable of accurately measuring the test duration within the allowable tolerance.

A1.6 Reagents and Materials

A1.6.1 Wax Solvent—2,2,4-trimethylpentane (isooctane) of minimum 99.75 % purity. (Warning—extremely flammable, see A1.7.)

A1.6.2 Surface Preparation/Polishing Materials, silicon carbide grit paper or cloth of varying degrees of fineness including 53 to 65-μm (240-grit) grade, also a supply of 105-μm (150-mesh) size silicon carbide grain or powder and absorbent cotton (cotton wool). A commercial grade is suitable, but pharmaceutical grade is most commonly available and is acceptable.

A1.6.3 Silver Strips Specification—Use strips 12.5 to 12.7-mm wide, 2.5 to 3.0-mm thick, and 17.0 to 19.0-mm long assaying at 99.9 % (m/m) Ag minimum. The strips may be used repeatedly but should be discarded when the strip's surface shows pitting or deep scratches that cannot be removed by the specified polishing procedure, or when the surface becomes deformed.

A1.6.4 Ashless Filter Paper or Disposable Gloves, for use in protecting the silver strip from coming in contact with the individual during final polishing.

A1.7 Hazards

A1.7.1 Isooctane:
Harmful if inhaled. Vapors may cause flash fire.
Keep away from heat, sparks, and open flame. Keep container closed.
Use with adequate ventilation.
Avoid build-up of vapors and eliminate all sources of ignition, especially nonexplosion-proof electrical apparatus and heaters.
Avoid prolonged breathing of vapor or spray mist.
Avoid prolonged or repeated skin contact.

A1.7.2 Gasoline (Unleaded or Leaded):
Keep away from heat, sparks, and open flame.
Keep container closed.
Use with adequate ventilation.
Avoid build-up of vapors and eliminate all sources of ignition, especially nonexplosion-proof electrical apparatus and heaters.
Avoid prolonged breathing of vapor or spray mist.
Avoid prolonged or repeated skin contact.

A1.8 Samples
A1.8.1 In accordance with Practice D 4057 or D 4177, or both, it is particularly important that all types of fuel samples, that pass a low-tarnish strip classification, be collected in clean, dark glass bottles, plastic bottles or other suitable containers that will not affect the corrosive properties of the fuel. Avoid the use of tin plate containers for collection of samples, since experience has shown that they may contribute to the corrosiveness of the sample.
A1.8.2 Fill the containers as completely as possible and close them immediately after taking the sample. Adequate headspace is the container is necessary to provide room for possible thermal expansion during storage. It is recommended that volatile samples be filled between 70 and 80 % of the container’s capacity. Take care during sampling to protect the samples from exposure to direct sunlight or even diffused daylight. Carry out the test as soon as possible after receipt in the laboratory and immediately after opening the container.
A1.8.3 If suspended water (that is, haze) is observed in the sample, dry by filtering a sufficient volume of sample through medium rapid qualitative filter paper, into the prescribed clean, dry test tube. Carry out this operation in a darkened room or under a light-protected shield.
A1.8.4.1 Contact of the silver strip with water before, during or after completion of the test run will cause staining, making it difficult to evaluate the strips.

A1.9 Preparation of Test Strips
A1.9.1 Surface Preparation—Remove all surface blemishes from all six sides of the strip obtained from a previous analysis (see Note A1.1). Use silicon carbide paper or cloth of such degrees of fineness as are needed to accomplish the desired results efficiently. Finish with 53 to 65-μm (240-grit) silicon carbide paper or cloth, removing all marks that may have been made by other grades of paper used previously. Immerse the strip in 2,2,4,trimethylpentane from which it can be withdrawn immediately for final preparation (polishing) or in which it can be stored for future use.

Note A1.1—Only final preparation (A1.9.2) is necessary for commercially purchased pre-polished strips.

A1.9.1.1 As a practical manual procedure for surface preparation, place a sheet of silicon carbide paper or cloth on a flat surface and moisten it with 2,2,4-trimethylpentane. Rub the strip against the silicon carbide paper or cloth with a circular motion, protecting the strip from contact with the fingers by using ashless filter paper or wearing disposable gloves. Alternatively, the surface of the strip can be prepared by use of motor-driven machines using appropriate grades of dry paper or cloth.

A1.9.2 Final Preparation—For strips prepared in A1.9.1 or new strips being used for the first time, remove a strip from the 2,2,4-trimethylpentane. To prevent possible surface contamination during final preparation, do not allow fingers to come in direct contact with the silver strips, by wearing disposable gloves or holding the strips in the fingers protected with ashless filter paper. Polish first the ends and then the sides with the 105-μm (150-mesh) silicon carbide grains or powder picked up with a pad of cotton (cotton wool) moistened with 2,2,4-trimethylpentane. Wipe vigorously with fresh pads of cotton (cotton wool) and subsequently handle without touching the surface of the strip with the fingers. Forceps have been found suitable to use. Clamp in a vise and polish the main surfaces with silicon-carbide grains on absorbent cotton. Do not polish in a circular motion. Rub in the direction of the long axis of the strip, carrying the stroke beyond the end of the strip before reversing the direction. Clean all metal dust from the strip by rubbing vigorously with clean pads of absorbent cotton until a fresh pad remains unsoiled. When the strip is clean, immediately immerse it in the prepared sample.

A1.9.2.1 It is important to polish the whole surface of the strip uniformly to obtain a uniformly stained strip. If the edges show wear (surface elliptical), they will likely show more corrosion than the center. The use of a vise (see Appendix X7) will facilitate uniform polishing.

A1.9.2.2 It is important to follow the order of preparation with the correctly sized silicon carbide material as described in A1.9.1 and A1.9.2. The final preparation is with 105-μm silicon carbide grains or powder. This is a larger grain size than the 53 to 65-μm paper used in the surface preparation stage. The reason for this use of larger silicon carbide grains in the final preparation is to produce asperities (controlled roughness) on the surface of the silver, which act as sites for the initiation of corrosion reactions.

A1.10 Procedure
A1.10.1 Pressure Vessel Procedure:
A1.10.1.1 Place 30 mL of sample, completely clear and free of any suspended or entrained water (see A1.8.3) into a chemically clean and dry 25-mm by 150-mm test tube. Within 1 min after completing the final preparation (polishing), slide the silver strip into the sample tube. Place the sample tube into the pressure vessel (Fig. A1.1) and screw the lid on tightly. If more than one sample is to be analyzed at essentially the same time, it is permissible to prepare each pressure vessel in the batch before completely immersing each pressure vessel in the liquid bath at 50 ± 1°C (122 ± 2°F), provided the elapsed time between the first and last samples is kept to a minimum. After 3 h ± 5 min in the bath, withdraw the pressure vessel and immerse for a few minutes in cool water (tap water). Open the pressure vessel, withdraw the test tube and examine the strip as described in A1.10.2.
\[ D 4814 - 09 \]

### TABLE A1.1 Silver Strip Classifications

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>No tarnish</td>
<td>Identical to a freshly polished strip, but may have some very light loss of luster</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slight tarnish</td>
<td>Faint brown or white discoloration of strip (see A1.11.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate tarnish</td>
<td>Peacock colors such as blue or mauve or medium dark straw or brown coloration (see A1.11.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy tarnish</td>
<td>Spots and patches of black or gray on surface or uniform thin film of black deposit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blackening</td>
<td>Uniform heavy blackening with or without scaling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A1.10.2 Strip Examination:

A1.10.2.1 Immediately withdraw the strip with forceps and immerse in 2,2,4-trimethylpentane. Withdraw the strip at once, dry it with ashless filter paper (by blotting not wiping) and inspect it for evidence of tarnishing or corrosion.

A1.10.2.2 In handling the test strip during the inspection and comparison, the danger of marking or staining can be avoided if it is inserted in a flat glass tube (see Appendix X7), which can be stopped with absorbent cotton.

A1.11 Interpretation of Results

A1.11.1 Interpret the corrosiveness of the sample by comparing the appearance of the test strip with a freshly polished one to give a classification based on that given in Table A1.1. All surfaces, including the edges, shall be taken into account.

A1.11.1.1 The Color Standard for Tube Deposit Rating (referenced in Test Method D 3241) shall be used to differentiate between the brown colorations mentioned in classifications 1 and 2. Any brown coloration less than No. 4 on the Color Standard shall be rated classification 1. Any coloration equal to or darker than No. 4 on the Color Standard shall be rated as classification 2 or higher.

A1.12 Report

A1.12.1 Report the corrosiveness in accordance with one of the classifications listed in Table A1.1. State the duration of the test and the test temperature in the following format:

\[ \text{Corrosion silver strip (Xh /°C), Classification Z} \] (A1.1)

where:

- \( X \) = test duration, in hours,
- \( Y \) = test temperature, °C, and
- \( Z \) = classification category (that is, 0, 1, 2, 3, or 4).

A1.13 Precision and Bias

A1.13.1 The precision and bias of this test method has not been determined.

### APPENDIXES

(Nonmandatory Information)

## XI. SIGNIFICANCE OF ASTM SPECIFICATION FOR AUTOMOTIVE SPARK-IGNITION ENGINE FUEL

### XI.1 General

XI.1.1 Anti-knock rating and volatility define the general characteristics of automotive spark-ignition engine fuel. Other characteristics relate to the following: limiting the concentration of undesirable components so that they will not adversely affect engine performance and ensuring the stability of fuel as well as its compatibility with materials used in engines and their fuel systems.

XI.1.2 Fuel for spark-ignition engines is a complex mixture composed of relatively volatile hydrocarbons that vary widely in their physical and chemical properties and may contain oxygenates. Fuel is exposed to a wide variety of mechanical, physical, and chemical environments. Thus, the properties of fuel must be balanced to give satisfactory engine performance over an extremely wide range of operating conditions. The prevailing standards for fuel represent compromises among the numerous quality and performance requirements. This ASTM specification is established on the basis of the broad experience and close cooperation of producers of fuel, manufacturers of automotive equipment, and users of both.

### XI.2 Engine Knock

XI.2.1 The fuel-air mixture in the cylinder of a spark-ignition engine will, under certain conditions, autoignite in localized areas ahead of the flame front that is progressing from the spark. This is engine spark knock which can cause a ping that may be audible to the customer.

XI.2.2 The antiknock rating of a fuel is a measure of its resistance to knock. The antiknock requirement of an engine depends on engine design and operation, as well as atmospheric conditions. Fuel with an antiknock rating higher than that required for knock-free operations does not improve performance.

XI.2.3 A decrease in antiknock rating may cause vehicle performance loss. However, vehicles equipped with knock limiters can show a performance improvement as the antiknock quality of the fuel is increased in the range between customer- audible knock and knock-free operation. The loss of power and the damage to an automotive engine due to knocking are generally not significant until the knock intensity becomes very severe. Heavy and prolonged knocking may cause power loss and damage to the engine.

### XI.3 Laboratory Octane Number

XI.3.1 The two recognized laboratory engine test methods for determining the antiknock rating of fuels are the Research method (Test Methods D 2699 or D 2885) and the Motor method (Test Methods D 2700 or D 2885). The following
paragraphs define the two methods and describe their significance as applied to various equipment and operating conditions.

X1.3.2 Research octane number is determined by a method that measures fuel antiknock level in a single-cylinder engine under mild operating conditions; namely, at a moderate inlet mixture temperature and a low engine speed. Research octane number tends to indicate fuel antiknock performance in engines at wide-open throttle and low-to-medium engine speeds.

X1.3.3 Motor octane number is determined by a method that measures fuel antiknock level in a single-cylinder engine under more severe operating conditions than those employed in the Research method; namely, at a higher inlet mixture temperature and at a higher engine speed. It indicates fuel antiknock performance in engines operating at wide-open throttle and high engine speeds. Also, Motor octane number tends to indicate fuel antiknock performance under partial-throttle, road-load conditions.

X1.4 Road Octane Number

X1.4.1 The road octane of a fuel is the measure of its ability to resist knock in customers' vehicles, and is ultimately of more importance than laboratory octane numbers. Since road octanes are difficult to measure and interpret, the industry has agreed to use ASTM laboratory engine tests to estimate the road octane performance of spark-ignition engine fuel in vehicles.

X1.4.2 The antiknock index (AKI) is the arithmetic average of the Research octane number (RON) and Motor octane number (MON):

$$\text{AKI} = \frac{(\text{RON} + \text{MON})}{2} \quad (X1.1)$$

This value is called by a variety of names, in addition to antiknock index, including:

- Octane rating
- Posted octane
- (R + M)/2 octane

X1.4.3 The AKI is posted on retail gasoline dispensing pumps in the United States and is referred to in car owners' manuals. The AKI is also required for certification at each wholesale fuel transfer and is referred to in United States federal law as "Octane Rating."

X1.4.4 The most extensive data base that relates the laboratory engine test methods for Research and Motor octane to actual field performance of fuel in vehicles is the annual Coordinating Research Council (CRC)\(^{11}\) Octane Number Requirement Survey conducted for new light-duty vehicles. Analysis of these data shows that the antiknock performance of a fuel in some vehicles may correlate best with Research octane number, while in others, it may correlate best with Motor octane number. These correlations also differ from model year to model year or from vehicle population to vehicle population, reflecting changes in engine designs over the years.

\(^{11}\text{Details of this regulation can be found in Code of Federal Regulations Title 49, Chapter I, Subchapter C, part 306/16 CFR306, U.S. Government Printing Office, Superintendent of Documents, Washington DC 20402.}\)


X1.4.5 The antiknock index of a fuel approximates the CRC road octane ratings for many vehicles. However, the user must also be guided by experience as to which fuel is most appropriate for an individual vehicle. The antiknock index formula is reviewed periodically and may have to be adjusted in the future as engines and fuels continue to evolve. The present (RON + MON)/2 formula is an estimate and is not an absolute measure of fuel antiknock performance in general or in any specific vehicle.

X1.4.6 Car antiknock requirements vary, even within a single model, so the statistical distribution of the octane needs of any car population are usually shown as a graphical form, as shown in Fig. X1.1. As antiknock index increases, larger and larger fractions of the car population in question will be free of knock, that is, be "satisfied" with the octane quality of fuels at or above that level of antiknock index. The data in Fig. X1.1 are for new model cars and trucks sold in the United States in the model year 1988 and are included as an example of the antiknock requirement distribution, not as a data reference.

X1.4.7 According to the winter 1988–1989 motor gasoline survey published by the National Institute for Petroleum and Energy Research, unleaded fuel antiknock indexes in current practice range from a low near 84 in the mountain areas to a high near 94. Companies typically market two or three unleaded grades of fuel, one of which usually has a minimum antiknock index of 87, for which most post-1971 vehicles are designed. Most companies also market a higher octane fuel with an antiknock index of 91 or above. This fuel is intended
TABLE X1.1 Automotive Spark-Ignition Engine Fuel Antiknock Indices in Current Practice

<table>
<thead>
<tr>
<th>Antiknock Index</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane No. (RON + MON)</td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>Designed to meet antiknock requirements of most 1971 and later model vehicles</td>
</tr>
<tr>
<td>89</td>
<td>Satisfies vehicles with somewhat higher antiknock requirements</td>
</tr>
<tr>
<td>91 and above</td>
<td>Satisfies vehicles with high antiknock requirements</td>
</tr>
<tr>
<td>Lead-Free Fuel (for vehicles that can or must use lead-free fuel)</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>For most vehicles that were designed to operate on lead-free fuel</td>
</tr>
</tbody>
</table>

Unleaded fuel having an antiknock index of at least 87 should also have a minimum Motor octane number of 82 in order to adequately protect those vehicles that are sensitive to Motor octave quality.

Reductions in vehicle antiknock requirements for altitude are shown in Fig. X1.2.

Reductions in vehicle antiknock requirements for seasonal variations are shown in Fig. X1.3.

Not all antiknock index levels listed in this table are available at all locations.


This page appears to be missing some content, possibly due to the page being blank or having a blank image. However, the text discusses automotive spark-ignition engine fuel antiknock indices in current practice, focusing on the grades and octane requirements, and mentions precision and bias of antiknock index determinations.

X1.4.8 Marketers set the grades and octane based on their perception of the technical and competitive needs in the market.

X1.4.9 Antiknock indexes of fuel sold in current practice in the United States are shown in Table X1.1 for both unleaded and leaded fuels.

X1.5 Precision and Bias of Antiknock Index

X1.5.1 The following statements apply to the precision and bias of antiknock index of fuel, which is a composite quantity not addressed in any other standard.

X1.5.2 The precision of the antiknock index, (RON + MON)/2, is a function of the individual precisions of Research (Test Method D 2699) and Motor (Test Method D 2700) octave numbers. The repeatability and reproducibility variances for these test methods are summed and divided by four to obtain the variance of the antiknock index.

X1.5.2.1 Repeatability—The difference between two sets of antiknock index determinations, where two test results by each octave number method were obtained by one operator, with the same apparatus under constant operating conditions on identical test material would, in the long run, and in the normal and correct operation of the test methods, exceed the values in the following table in only one case in twenty.

X1.5.2.2 Reproducibility—The difference between two independent sets of antiknock index determinations, obtained by different operators working in different laboratories on identical test material would, in the long run, and in the normal and correct operation of the test methods, exceed the values in the following table in only one case in twenty.

Note X1.1—These precision values were calculated from Research and Motor octave number results utilizing exchange sample test data obtained by the ASTM National Exchange Group (NEG), the Institute of Petroleum, or the Institut Français du Petrole, or combination thereof, participating in cooperative testing programs. The precision values for 83, 85, 87, 91, 93, 95, and 97 AKI were obtained from NEG data during the period 1980 through 1982 and have been analyzed in accordance with RR: D02-1007, "Manual on Determining Precision Data for ASTM Methods on Petroleum Products and Lubricants," Spring 1973. The precision values for 87 through 93 AKI were calculated using the data from RR: D02-1383, "Research and Motor Octane Number Precision Study Report, 1988 through 1994," December 1995.11

X1.5.2.3 Bias—Since knock ratings are determined by the conditions of the empirical test methods involved, bias cannot be determined.

11 Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR: D02-1007.
12 Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR: D02-1383.
X1.6 Effects of Altitude and Weather on Vehicle Antiknock Requirement

X1.6.1 A vehicle’s antiknock requirement can vary with changes in altitude, ambient temperature, and humidity, depending on the control system of the vehicle. New vehicles have sensors to measure and engine management computers, which take into account such conditions as air charge temperature and barometric pressure. These vehicles are designed to have the same antiknock requirement at all altitudes and a reduced sensitivity to changes in ambient temperature. This more sophisticated control technology began to be used extensively in 1984. This technology, while constantly evolving and improving, is used on almost all new vehicles. This means that many vehicles in today’s fleet require fuel having the same antiknock index regardless of changes in altitude or ambient temperatures. Older vehicles, which do not have sophisticated control systems, will likely experience changes in antiknock requirement due to changes in altitude and weather conditions. However, the changes in antiknock requirement indicated in the following sections apply to a continually smaller part of the vehicle fleet.

X1.6.2 The antiknock requirement of an older vehicle decreases as altitude increases, primarily due to reduction in mixture density caused by reduced atmospheric pressure. The change in antiknock requirement for altitude for older vehicles is given in Fig. X1.12. Boundaries of the areas defined and the corresponding antiknock index reductions were established to protect vehicles driven from a higher altitude to a lower altitude (and hence higher antiknock requirement) area while using a fuel obtained in the high altitude area.

X1.6.3 Tests by CRC and other organizations have shown that the decrease in antiknock requirements with altitude is larger for most models between 1971 and 1984, designed to use a fuel with an antiknock index of 87, than for pre-1971 vehicles. Generally the pre-1971 vehicles have high compression ratios and were designed for fuels with an antiknock index of 88 or higher. Fuels with antiknock indexes below 89 are adjusted by a larger factor than those with an antiknock index of 89 or greater.

X1.6.4 The antiknock requirements of older vehicles rise with increasing ambient temperature on the average by 0.097 MON per degree Celsius (0.054 MON per degree Fahrenheit).

X1.6.5 The antiknock requirements of both older and new vehicles decrease with increasing specific humidity by 0.245 MON per gram of water per kilogram of dry air (0.05 MON per gram of water per pound of dry air).

X1.6.6 Because temperature and humidity of geographical areas are predictable throughout the year from past weather records, antiknock index levels can be adjusted to match seasonal changes in vehicle antiknock requirements. Fig. X1.13 defines the boundaries of areas and the typical reduction in vehicle antiknock requirements for weather for older vehicles. This figure may not apply to newer vehicles.

X1.7 Leaded Versus Unleaded Fuel Needs

X1.7.1 In addition to selecting the appropriate antiknock index to meet vehicle antiknock needs, a choice must be made between leaded and unleaded fuel. Vehicles that must use unleaded fuel are required by Environmental Protection Agency regulation to have permanent labels on the instrument panel and adjacent to the fuel tank filler inlet reading “Unleaded Fuel Only.” Most 1975 and later model passenger cars and light trucks are in this category. Most 1971-1974 vehicles can use leaded or unleaded fuel. Pre-1971 vehicles were designed for leaded fuel; however, unleaded fuel of suitable antiknock index may generally be used in these vehicles, except that leaded fuel should be used periodically (after a few tankfuls of unleaded fuel have been used). Leaded fuel may be required in some vehicles, particularly trucks, in heavy-duty service and some farm equipment. Instructions on fuel selection are normally provided in publications of vehicle manufacturers (for example, owner’s manuals, service bulletins, and so forth). Antiknock agents other than lead alkyls may be used to increase the antiknock index of fuels, and their concentrations may also be limited due to either performance or legal requirements.

X1.8 Volatility

X1.8.1 In most spark-ignition internal combustion engines, the fuel is metered in liquid form through the carburetor or fuel injector, and is mixed with air and partially vaporized before entering the cylinders of the engine. Consequently, volatility is an extremely important characteristic of motor fuel.

X1.8.2 At high operating temperatures, fuels can boil in fuel pumps, lines, or carburetors. If too much vapor is formed, the fuel flow to the engine can be decreased, resulting in loss of power, rough engine operation, or engine stoppage. These conditions are known as “vapor lock.” Conversely, fuels that do not vaporize sufficiently can cause hard starting of cold engines and poor warm-up performance. These conditions can
be minimized by proper selection of volatility requirements, but cannot always be avoided. For example, during spring and fall, a fuel of volatility suitable for satisfactory starting at low ambient temperatures can cause problems in some engines under higher ambient temperature operating conditions.

X1.8.3 Six vapor pressure/distillation classes and six vapor lock protection (vapor-liquid ratio) classes of fuel are provided to satisfy vehicle performance requirements under different climatic conditions and to comply with U.S. EPA vapor pressure limits for the control period of May 1 through September 15. Class A and Class AA specify the EPA maximum vapor pressure limits of 9.0 psi and 7.8 psi, respectively. Volatility of fuel is specified by an alphanumeric designation. The letter specifies the vapor pressure/distillation class and the number specifies the vapor lock protection class. The vapor pressure/distillation classes are needed to comply with the EPA vapor pressure regulations and are not based on vehicle performance during the EPA control period. The separate vapor lock protection classes are provided because under most ambient conditions, the EPA regulations specify a lower vapor pressure than would be required to prevent hot fuel handling problems. If the corresponding and unnecessarily more restrictive vapor-liquid ratios were specified when the EPA regulations are in effect, it could result in reduced fuel production, manufacturing hardships, and increased fuel costs. The schedule for seasonal and geographical distribution indicates the appropriate alphanumeric volatility requirement or requirements for each month in all areas of the United States, based on altitude and expected air temperatures, and on EPA vapor pressure regulations. Volatility limits are established in terms of vapor-liquid ratio, vapor pressure, and distillation properties.

X1.8.4 For sea-level areas outside of the United States where vapor pressure requirements are not as restrictive as those specified by EPA, the following ambient temperatures are for guidance in selecting the appropriate alphanumeric designations:

<table>
<thead>
<tr>
<th>Alphabet</th>
<th>10th Percentile</th>
<th>90th Percentile</th>
<th>Volatility Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16 (60)</td>
<td>&gt;43 (100)</td>
<td>A-1</td>
</tr>
<tr>
<td>2</td>
<td>&gt;10 (50)</td>
<td>&gt;43 (100)</td>
<td>B-2</td>
</tr>
<tr>
<td>3</td>
<td>&gt;4 (45)</td>
<td>&gt;29 (80)</td>
<td>C-3</td>
</tr>
<tr>
<td>4</td>
<td>&gt;7 (20)</td>
<td>&gt;21 (80)</td>
<td>D-4</td>
</tr>
<tr>
<td>5</td>
<td>&gt;7 (20)</td>
<td>21 (86)</td>
<td>E-5</td>
</tr>
</tbody>
</table>

The 6-h minimum temperature is the highest temperature of the six coldest consecutive hourly temperature readings of a 24-h day. The 6-h minimum temperature provides information on the cold-soak temperature experienced by a vehicle. The 10th percentile of this temperature statistic indicates a 10% expectation that the 6-h minimum temperature will be below this value during a month. The 90th percentile maximum temperature is the highest temperature expected during 90% of the days, and provides information relative to peak vehicle operating temperatures during warm and hot weather. For areas above sea level, the 10th percentile 6-h minimum temperature should be increased by 3.6 °C/1000 m (2.4°F/1000 ft) of altitude, and the 90th percentile maximum should be increased by 4.4°C/1000 m (2.4°F/1000 ft) of altitude before comparing them to the sea level temperature. These corrections compensate for changes in fuel volatility caused by changes in barometric pressure due to altitude.

X1.9 Vapor Pressure

X1.9.1 The vapor pressure of fuel must be sufficiently high to ensure ease of engine starting, but it must not be so high as to contribute to vapor lock or excessive evaporative emissions and running losses.

X1.9.2 Test Methods D 4953, D 5190, D 5191, or D 5482 provide procedures for determining the vapor pressures of gasoline or gasoline-oxygenate blends.

X1.10 Vapor-Liquid Ratio

X1.10.1 Vapor-liquid ratio (V/L) is the ratio of the volume of vapor formed at atmospheric pressure to the volume of fuel. The V/L increases with temperature for a given fuel. Test Method D 5188 is an evacuated chamber method for determining temperatures for vapor-liquid ratios between 8 to 1 and 75 to 1. Test Method D 5188 is applicable to both gasoline and gasoline-oxygenate blends.

X1.10.2 The temperature of the fuel system and the V/L that can be tolerated without vapor lock or hot fuel handling problems vary from vehicle to vehicle and with operating conditions. The tendency of a fuel to cause vapor lock or hot fuel handling problems, as evidenced by loss of power during full-throttle accelerations or hot starting and idling problems, is indicated by the gasoline temperature at a V/L of approximately 20. A similar relationship for gasoline-oxygenate blend has also been determined. The minimum temperature at which V/L = 20 is specified for each gasoline volatility class is based on the ambient temperatures and the altitude associated with the use of the class.

X1.11 Vapor-Liquid Ratio (Estimated)

X1.11.1 Two techniques for estimating temperature-V/L values using vapor pressure (Test Methods D 4953, D 5190, D 5191, or D 5482) and distillation (Test Method D 86) results are given in Appendix X2; they apply to only gasoline and gasoline-oxygenate blends containing from 1 to 10 volume % ethanol.

X1.12 Distillation

X1.12.1 Test Method D 86 for distillation provides another measure of the volatility of fuels. Table 1 designates the limits for endpoint temperature and the temperatures at which 10%, 50%, and 90% by volume of the fuel is evaporated. These distillation characteristics, along with vapor pressure and V/L characteristics, affect the following vehicle performance characteristics: starting, driveability, vapor lock, diution of the engine oil, fuel economy, and carburetor icing.

X1.12.2 The 10% evaporated temperature of fuel should be low enough to ensure starting under normal temperatures.

X1.12.3 Fuels having the same 10% and 90% evaporated temperatures can vary considerably in driveability performance because of differences in the boiling temperatures of the intermediate components, or fractions. Driveability and idling quality are affected by the 50% evaporated temperature.
90 % evaporated and endpoint temperatures should be low enough to minimize dilution of the engine oil.

X1.12.4 The ASTM Driveability Task Force has determined from data collected by CRC and others that a relationship exists between fuel distillation temperatures and vehicle cold start and warm-up driveability performance. This relationship can be expressed by a Driveability Demerit model that can estimate vehicle driveability demerits during cold start and warm-up conditions. The predictive model is a function of ambient temperature and fuel volatility expressed as the distillation temperatures at which 10 %, 50 %, and 90 % by volume of the fuel is evaporated. The original Driveability Index (DI = 1.5 T10 + 3.0 T50 + 1.0 T90) is a simplified and more easily applied form of the Driveability Demerit model. A more detailed explanation of the DI equation development can be found in SAE Paper 881668. More recent CRC driveability studies have investigated the effect of ethanol addition on cold start and warm-up driveability. The ASTM Driveability Task Force decided that an upward adjustment for ethanol is needed in the DI equation as follows:

\[ DI = 1.5 T_{10} + 3.0 T_{50} + 1.0 T_{90} + 1.23^\circ C (2.2^\circ F) \times \text{Ethanol Volume \%}, \]

as shown in Table 4,

where:

- 1.33 = coefficient for the volume % ethanol present when the distillation results are determined in degrees Celsius, and
- 2.4 = coefficient when the distillation results are determined in degrees Fahrenheit.

X1.12.5 A typical distillation curve of gasoline containing only hydrocarbon molecules has a smooth and steady upward slope between the 10 % and 90 % evaporated temperatures. Gasoline containing ethanol at 5 to 10 volume % will display a distillation curve with a much decreased slope between the 30 % and 50 % evaporated temperatures that rejoins the expected slope once all the ethanol has distilled off. The lower the ethanol content, the sooner this part of the distillation curve rejoins the expected slope. Addition of certain hydrocarbon components to streams in large quantities to gasoline can cause a hump in the part of the distillation range where the hydrocarbon boils. For example, high levels of certain blending components (such as reformate) can cause the distillation curve to have a hump between the 50 % and 90 % evaporated temperatures that is centered at the 70 % evaporated temperature. In some cases, the lack of material boiling in this temperature range can result in a distillation curve that resembles a dumbbell. Elevated distillation temperatures result in a less volatile fuel, which can affect vehicle driveability while it is in open loop operation. For vehicles calibrated to the latest emissions standards, excess fuel is injected during startup to ensure a quick start, but as soon as the engine engages, fueling is cut back quickly to minimize emissions while the catalyst warms up. If the volatility of the fuel is lower than expected, the cut back in fuel can be too extreme, resulting in a lean air-fuel mixture delivered to the cylinders. A misfire can result that is manifested as a driveability problem. During open loop operation, a vehicle relies on the ECM for a standard fueling strategy, and it cannot adjust the air-fuel mixture until closed loop operation begins, which is about 30 s after startup for the newest vehicles, and up to several minutes for older vehicles.

The extent of a fuel’s deviation from a normal distillation slope can be quantified by determining the difference between the measured 70 % evaporated temperatures and a calculated value, which is approximated by the arithmetic average of the 50 % and 90 % evaporated temperatures. Vehicle testing has shown if the difference between the measured and calculated 70 % evaporated temperature is less than 12°C (22°F), average vehicle driveability, as measured by trained raters is comparable to fuel with standards distillation curve. When the difference is greater than 12°C (22°F), average vehicle driveability is degraded. The difference is determined using the following equation:

\[ T_{90} \text{ Bump Difference} = \frac{T_{50} - (T_{90} + T_{10})}{2} \]  

\[ T_{50} = 50 \% \text{ evaporated distillation temperatures, as determined by Test Method D 86} \]

\[ T_{90} = 90 \% \text{ evaporated distillation temperatures, as determined by Test Method D 86} \]

X1.13 Corrosion

X1.13.1 Fuels must pass the copper strip corrosion test to minimize corrosion in fuel systems due to sulfur compounds in the fuel. Some fuels corrode fuel system metals other than copper, but there are no ASTM test methods to evaluate corrosion of these metals. Depending on the type and concentration of oxygenate, gasoline-oxygenate blends can corrode metals such as zinc, magnesium, aluminum, steel, and termite. However, at this time there is no test method with a known correlation to field performance. Consequently, additional corrosion tests are needed.

X1.13.2 Reactive sulfur compounds present in automotive spark-ignition engine fuel under some circumstances can corrode or tarnish silver alloy fuel gauge in-tank sender units. To minimize the failure of silver alloy in-tank sender units by corrosion or tarnish, fuels must pass the silver strip corrosion test.

X1.14 Solvent-Washed Gum Content

X1.14.1 The test for solvent-washed gum content measures the amount of residue after evaporation of the fuel and following a heptane wash. The heptane wash removes the heptane-insoluble, non-volatile material such as additives, carrier oils used with additives, and heavier hydrocarbons such as diesel fuels, and so forth. Solvent-washed gum consists of fuel-insoluble gum and fuel-soluble gum. The fuel-insoluble portion can clog fuel filters. Both can be deposited on surfaces when the fuel evaporates.
X.14.2 Solvent-washed gum can contribute to deposits on the surfaces of carburetors, fuel injectors, and intake manifolds, ports, valves, and valve guides. The impact of solvent-washed gum on malfunctions of modern engines is not well established and the current specification limit is historic rather than the result of recent correlative studies. It depends on where the deposits form; the presence of other deposit precursors, such as airborne debris, blowby and exhaust gas recirculation gases, and oxidized engine oil; and the amount of deposits.

X.14.3 The difference between the unwashed and solvent-washed gum content values can be used to assess the presence and amount of nonvolatile material in the fuel. Additional analytical testing is required to determine if the material is additive, carrier oil, diesel fuel, and so forth.

X.2 ESTIMATING TEMPERATURE-V/L VALUES FOR GASOLINE

X.2.1 Scope
X.2.1.1 Two techniques are presented here for estimating temperature-V/L data from vapor pressure and distillation test results. They are provided for use as a guideline when V/L data measured by Test Method D 5188 are not available. One method is designed for computer processing and one is a simpler linear technique. The techniques were originally only applicable to gasoline and not to gasoline-oxygenate blends. A program was undertaken to modify the techniques to make them also applicable to gasoline-oxygenate blends (1 to 10 volume %).

X.2.1.2 These techniques are not optional procedures for measuring temperature-V/L. They are supplementary tools for estimating temperature-V/L relationships with reasonable accuracy when used with due regard for their limitations.

X.2.1.3 Test Method D 5188 is the reference V/L procedure and shall be used when calculated values are questionable.

X.2.1.4 These techniques are not intended for, nor are they necessarily applicable to, fuels of extreme distillation or chemical characteristics, such as would be outside the range of normal commercial motor gasoline or gasoline-oxygenate blends. Thus, they are not applicable in all instances to gasoline blending stocks or specially blended fuels.

X.2.2 Computer Method
X.2.2.1 Summary—The values of four intermediate functions, A, B, C, and D, are derived from the gasoline vapor pressure and distillation temperatures at 10, 20, and 50 % evaporated. Values for A, B, C, and D can be obtained either from equations or from a set of charts. Sections X.2.2.1-X.2.2.3 provide A, B, C, and D values using SI units; X.2.2.7-X.2.2.9 provide A, B, C, and D values using in-ch. pound units. Estimated temperatures at a V/L of 4, 10, 20, 30, and 45 are then calculated from A, B, C, and D. Estimated temperatures at an intermediate V/L can be obtained by interpolation.

X.2.2.2 Procedure
X.2.2.2.1 Establish input data from vapor pressure (Test Methods D 4953, D 5190, D 5191, or D 5482) and distillation (Test Method D 86) test results as follows:

\[ E = \text{distillation temperature, } ^\circ F \text{ at } 10 \% \text{ evaporated,} \]
\[ F = \text{distillation temperature, } ^\circ F \text{ at } 20 \% \text{ evaporated,} \]
\[ G = \text{distillation temperature, } ^\circ F \text{ at } 50 \% \text{ evaporated,} \]
\[ H = G - E, ^\circ F, \]
\[ P = \text{vapor pressure, kPa}, \]
\[ Q = F - E, ^\circ F, \text{ and} \]
\[ R = H/Q, \text{ except that if } H/Q \text{ is greater than } 6.7, \text{ make } R = 6.7. \]

X.2.2.2.2 If A, B, C, and D are to be calculated, use the following equations:

\[ A = 102.859 - 1.26599P + 0.999417P^2 - 0.000028281P^3 + 207.0971P \]
\[ B = -0.36105 + 0.91054Q - 0.01917G' + 0.00957774Q^2 + 0.254183Q \]
\[ S = -0.000052549 - 0.367136(P - 9.65) - 0.112419P - 9.65 \]
\[ + 0.0009677P - 0.000015928P^2 \]
\[ + 124.1381P \]
\[ + 0.00639129P^2 + 0.0002789P^3 + 0.0096153P^4 \]
\[ C = 0.34205P + 0.55556P \]
\[ B = 0.62478 + 0.68964P + 0.132708P^2 \]
\[ - 0.007017P + 5.8585P \]

X.2.2.2.3 If A, B, C, and D are to be obtained from charts, read them from Fig. X.2.1, Fig. X.2.2, Fig. X.2.3, or Fig. X.2.4, respectively.
X2.2.2.4 Calculate the estimated temperature (°C or °F) at V/L ratios 4, 10, 20, 30, and 45 from the following equations:

\[ TVL = A + B \]  
\[ TVL_{45} = F + 0.125H + C \]  
\[ TVL_{10} = TVL + 0.146541 (TVL_{10} - TVL) + D \]  
\[ TVL_{20} = TVL + 0.39244 (TVL_{20} - TVL) + 1.46514D \]  
\[ TVL_{30} = TVL + 0.634146 (TVL_{30} - TVL) + D \]  

where:

TVL4, TVL10, TVL20, TVL30, and TVL45 are estimated temperatures at V/L ratios of 4, 10, 20, 30, and 45, respectively.

X2.2.2.5 If the temperature at an intermediate V/L ratio is to be estimated, either plot the values calculated in X2.2.2.4 and read the desired value from a smooth curve through the points, or use the Lagrange interpolation formula as follows:

\[ TX = T4 \left( \frac{X-4}{10-4} \right) + T10 \left( \frac{X-10}{10-4} \right) + T30 \left( \frac{X-30}{10-4} \right) + T45 \left( \frac{X-45}{10-4} \right) \]  

where:

\[ X = \] the desired V/L ratio between 4 and 45, and

\[ TX = \] the estimated temperature at V/L ratio X.

X2.2.2.6 Temperature-V/L = 20 (TVL_{20})—To calculate an estimated TVL_{20} in SI units for gasoline, use the TVL20 value from X2.2.2.4 (Eq X2.12) or for gasoline-ethanol blends, insert the TVL20 value determined in X2.2.2.4 (Eq X2.12) into Eq X2.15 and make the calculation.

X2.2.2.7 If inch-pound units are used, establish input data from vapor pressure (Test Methods D 4953, D 5190, D 5191, or D 5482) and distillation (Test Method D 86) test results as follows:

\[ E = \] distillation temperature, °F at 10% evaporated,

\[ F = \] distillation temperature, °F at 20% evaporated,

\[ G = \] distillation temperature, °F at 50% evaporated,

\[ H = G - E, °F \]  

\[ P = \] vapor pressure, psi,

\[ Q = F - E, °F, \] and

\[ R = HQ, \] except that if HQ is greater than 6.7, make \( R = 6.7 \).

X2.2.2.8 If A, B, C, and D are to be calculated in inch-pound units, use the following equations:

\[ A = 217.147 - 16.9527P + 0.822099P^2 - 0.0166849P^3 + 54.0436P \]  
\[ B = -9.96863 + 0.910549Q - 0.0223626Q^2 + 0.0000718314Q^3 \]  
\[ C = 1.14560 - 0.941335R + 0.238837R^2 \]  
\[ D = -0.0167950P^2 + 10.5273R \]

X2.2.2.9 If A, B, C, and D are to be obtained from charts in inch-pound units, read them from Figs. X2.2.5-X2.2.8, respectively.

X2.2.2.10 Calculate the estimated temperatures, °F, at V/L ratios 4, 10, 20, 30, and 45 using the equations in X2.2.2.4 and X2.2.2.5.

X2.2.2.11 Temperature-V/L = 20 (TVL_{20})—To calculate an estimated TVL_{20} in inch-pound customary units for gasoline, use the TVL20 value from X2.2.2.4 or for gasoline-ethanol blends, insert the TVL20 value determined in X2.2.2.4 into Eq X2.24 and make the calculation.

X2.3 Linear Equation Method

X2.3.1 Summary—As given, these two equations provide only the temperatures (°C or °F) at which a V/L value of 20 exists. They make use of two points from the distillation curve, TVP and TVS (°C or °F), and the vapor pressure (kPa or psi) of the gasoline with constant weighting factors being applied to each. Experience has shown that data obtained with these simple linear equations generally are in close agreement with those obtained by the computerized version given above. The limitations pointed out in X2.1.1-X2.1.4 must be kept in mind when use is made of this procedure.

X2.3.2 Procedure—Obtain 10% evaporated and 50% evaporated points from the distillation curve (Test Method D 86) along with the vapor pressure value (Test Methods D 4953, D 5190, D 5191, or D 5482); apply these directly in the equation.

\[ TVL_{20} = 52.47 - 0.33 (VP) + 0.20 T_{10} + 0.17 T_{50} \]  

where:

\[ TVL_{20} = \] intermediate temperature, °C, at V/L of 20:1,

\[ VP = \] vapor pressure, kPa,

\[ T_{10} = \] distillation temperature, °C, at 10% evaporated, and

\[ T_{50} = \] distillation temperature, °C, at 50% evaporated.

or in the inch-pound customary unit equation:

\[ TVL_{20} = 114.6 - 4.1 (VP) + 0.20 T_{10} + 0.17 T_{50} \]  

where:

\[ TVL_{20} = \] intermediate temperature, °F, at V/L of 20:1,

\[ VP = \] vapor pressure, psi,

\[ T_{10} = \] distillation temperature, °F, at 10% evaporated, and

\[ T_{50} = \] distillation temperature, °F, at 50% evaporated.

X2.3.3 Temperature-V/L = 20 (TVL_{20})—To calculate an estimated TVL_{20} for gasoline, use the value for TVL20 value determined in X2.3.2 (SI Eq X2.25 or inch-pound Eq X2.26) or...
for gasoline-ethanol blends, insert the TVL.20 values determined in X2.3.3 (SI or inch-pound as appropriate) into Eq X2.27 for SI units and Eq X2.28 for inch-pound customary units.

(SI units) Gasoline–ethanol blend $T_{\text{ref}} = 20 - 0.782(T_{\text{VLL}}) + 10.57$

(INCH-POUND UNITS) Gasoline–ethanol blend $T_{\text{ref}} = 20 - 0.782(T_{\text{VLL}}) + 20.00$

X2.4 Precision

X2.4.1 The precision of agreement between temperature-V/I data estimated by any one of these two techniques and data obtained by Test Method D 5188 has not been established. An estimate of the reproducibility of the two calculation techniques reported in the research report as ranging from 2.1 to 1.0°C (3.8 to 1.8°F) for the computer method and 1.9 to 0.8°C (3.5 to 1.5°F) for the linear method as $T_{\text{VLL}} = 20$ increased from 43 to 66°C (110 to 150°F).
X3. SUMMARY OF EPA REGULATIONS APPLICABLE TO SPARK-IGNITION ENGINE FUEL

X3.1 EPA Applicable Vapor Pressure Standards

X3.1.1 Under authority of the Clean Air Act, the U.S. Environmental Protection Agency (EPA) issued, effective May 1992, vapor pressure control standards for leaded and unleaded gasoline and leaded and unleaded gasoline-oxygenate blends. Some states, notably California, have more restrictive vapor pressure limits.

X3.1.2 Details of the EPA regulations and test methods are available in Part 80 of Title 40 of the Code of Federal Regulations (40 CFR Part 80). For specific state vapor pressure regulations, the state of interest should be contacted.

X3.1.3 The EPA maximum vapor pressure limits of 7.8 psi and 9.0 psi are shown in Table 1 as Classes AA and A, respectively. The EPA requirements for each distribution area are shown in Table 4 for the period May 1 through September 15. For the month of May, the EPA limits only apply to finished gasoline and gasoline-oxygenate blend tankage at refineries, importers, pipelines, and terminals. For the period June 1 through September 15, the EPA limits apply to all locations of the distribution system. Footnotes C, D, and F of Table 4 indicate the ozone nonattainment areas which are limited to 7.8 psi maximum and the appropriate vapor lock protection class. California has controls that vary for the different air basins from as early as March 1 at refineries through as late as October 31. There are no EPA vapor pressure limits for the states of Alaska or Hawaii.

X3.1.4 EPA regulations allow 1.0 psi higher values for gasoline-oxygenate blends than the EPA limits shown in Table 1 and Table 4 for the period May 1 through September 15. To qualify, the gasoline-oxygenate blends must contain 9 to 10 volume% ethanol. Higher vapor pressure limits for gasoline-oxygenate blends under state regulations vary for other time...
periods, and specific states of interest should be contacted to determine if higher limits apply.

X.3.2 EPA Lead and Phosphorus Regulations

X.3.2.1 Unleaded Fuel—The intentional addition of lead or phosphorus compounds to unleaded fuel is not permitted by the EPA. EPA regulations limit their maximum concentrations to 0.05 g lead/U.S. gal (0.013 g/L) and 0.005 g of phosphorus/U.S. gal (0.0013 g/L) (see Test Method D 3231), respectively.

X.3.2.2 Lead—EPA regulations after December 31, 1995 prohibit the sale, supply, dispensing, transporting, or introducing into commerce a fuel for use in any motor vehicle which is produced with the use of lead additives or which contains more than 0.05 g lead/U.S. gal (0.013 g/L).

X.3.2.2.1 The regulations define motor vehicle to include any self-propelled vehicle designed for transporting persons or property on a street or highway.

X.3.2.2.2 The regulations do not prohibit the use of lead additives in fuel used in aircraft, racing cars, and nonroad engines, such as farm equipment engines and marine engines.

X.3.3 EPA Oxygenate Regulations Applicable to Unleaded Gasoline-Oxygenate Blends

X.3.3.1 Substantially Similar Rule:

X.3.3.1.1 Section 211(f) (1) of the Clean Air Act prohibits introducing into commerce or increasing the concentration in use of, any fuel or fuel additive, which is not substantially similar to any fuel or fuel additive utilized for emissions certification of any model year 1975, or subsequent model year vehicle or engine, unless a waiver is obtained from the EPA.

X.3.3.1.2 Gasoline-oxygenate blends are considered “substantially similar” if the following criteria are met:

1. The fuel must contain carbon, hydrogen, and oxygen, nitrogen, or sulfur, or combination thereof, exclusively, in the form of some combination of the following:
   a. Hydrocarbons;
   b. Aliphatic ethers;
   c. Aliphatic alcohols other than methanol;
   d. (i) Up to 0.3 volume % methanol;
      (ii) Up to 2.75 volume % methanol with an equal volume of butanol, or higher molecular weight alcohol;

2. The fuel must contain no more than 2.0 mass % oxygen except fuels containing aliphatic ethers and/or alcohols (excluding methanol) must contain no more than 2.7 mass % oxygen.

3. The fuel must possess, at the time of manufacture, all of the physical and chemical characteristics of an unleaded gasoline as specified by Specification D 4814 – 88 for at least one of the Seasonal and Geographical Volatility Classes specified in the standard.

X.3.3.2 Waivers:

X.3.3.2.1 EPA has issued waivers for blends of gasoline and ethanol (gasohol), gasoline and ethanol with cosolvents, and gasoline and methanol with cosolvents that are less limiting than the “substantially similar” rule. For the latest listing of waivers, the EPA should be contacted.

X.3.3.2.2 Gasoline-ethanol blends are not required by EPA to meet Specification D 4814 volatility limits (see X.3.1.4 for pressure limits). EPA has specified in all other waivers that the volatility of the finished gasoline-oxygenate blend must comply with Specification D +39 or D 4814 climatic and geographical limits.

X.3.4 EPA Reformulated Gasoline (RFG)

X.3.4.1 Reformulated gasoline (RFG) is a spark-ignition engine fuel formulated to reduce motor vehicle emissions of toxic and tropospheric ozone-forming compounds. The Clean Air Act Amendments of 1990 require that RFG be sold in nine metropolitan areas with the worst summertime ozone levels. Other areas that do not meet ambient ozone standards may petition EPA to require RFG. The various RFG regulations have been established by the EPA. EPA has also placed limits on conventional gasoline sold in the rest of the U.S. to prevent RFG producers from using conventional gasoline as an outlet for undesirable fuel components (anti-dumping requirements). The EPA requirements became effective at the retail level on January 1, 1995.

X.3.4.2 The characteristics of reformulated spark-ignition engine fuel, beyond those described by this specification, are described in the research report on reformulated spark-ignition engine fuel. The research report also includes information on California Air Resources Board Phase 2 gasoline requirements, which are more restrictive than the EPA RFG requirements and take effect at the retail level on June 1, 1996.

X.3.5 EPA Certification Standards for Deposit Control Gasoline Additives

X.3.5.1 Beginning August 1, 1997, except for some fuel specific certifications, fuel sold or transferred to the ultimate consumer must contain detergent additive(s) meeting the EPA certification requirements. The regulation applies to fuels whether intended for on-highway or nonroad use, including conventional, reformulated, oxygenated, and leaded gasolines, as well as fuels used in marine service, and the gasoline component of MB85 and EB85 fuel alcohols. Racing fuel for non-highway use in racing vehicles and aviation fuel used in aircraft are exempted. Fuels used for research, development, and testing and federal emissions certification fuels can be exempted.

X.3.5.2 As of July 1, 1997, only certified detergents may be used by detergent blenders, and distributors may only sell or transfer fuel that is properly additized with certified detergents. Detergent additives may be certified for nationwide use, for geographical use based on Petroleum Administration Districts for Defense (PADD), or for a fuel-specific option for segregated gasoline pools. Certification sub-options allow a detergent to be certified for use in premium-grade, nonoxygenated, or oxygenate-specific fuel. A California Air Resources Board additive certification will be accepted for fuel additized or used only in California. Specific minimum fuel properties (aromatics, sulfur content, olefins content, and 90 % evaporated point) for each option are required for certification and the certification fuels must also meet the requirements of Specification D 4814-95c. For some options, the addition of 10 volume % ethanol is required for certification fuel. Other oxygenates may also be required. Testing is required to demonstrate that the certification fuels without additives form a minimum level of intake valve deposits if specially formulated from refinery
blend stocks. Such deposit demonstration testing is not required for test fuels sampled directly from finished fuels, fuel-specific test fuels, CARB-based certifications, and leaded gasoline certifications.

X3.5.3 For additive certification, the test fuel containing the detergent additive(s) must form less than 100 mg/valve average intake valve deposit weight after 10,000 miles of testing in accordance with Test Method D 5500-94. In addition, after 10,000 miles of testing, there may be no more than 5% flow restriction is any one fuel injector in accordance with Test Method D 5598-94.

X3.6 EPA Gasoline Sulfur Requirements (Tier 2)

X3.6.1 Beginning in 2004, the basic EPA sulfur regulations require refiners to meet a corporate pool annual average sulfur maximum level of 120 parts per million (ppm), with a per gallon cap of 300 ppm. A provision in the rules allows a refinery to exceed the 300 ppm cap up to a maximum of 350 ppm for 2004. EPA has taken into account a 28 ppm test reproducibility which translates into a downstream enforcement standard of 378 ppm maximum (350+26). Anyone taking advantage of producing gasoline in excess of 300 ppm has to make up for the excess in their 2005 cap. For 2005, the corporate pool annual average decreases to 90 ppm maximum, the per gallon cap is at 300 ppm, and a refinery annual average maximum limit of 30 ppm is added. The downstream enforcement standard lowers to 256 ppm (300 ppm refinery cap plus 26 ppm test reproducibility). For 2006 and later, the refinery annual average remains at 30 ppm maximum, the per gallon cap is reduced to 80 ppm, and there no longer is a corporate pool annual average limit. The downstream enforcement standard is reduced to 95 ppm maximum (80 ppm refinery cap plus 15 ppm test reproducibility).

X3.6.2 Also beginning in 2004, there is a separate set of standards for a Geographical Phase-In Area Program (GPA) which consists of the states of Alaska, Colorado, Idaho, Montana, New Mexico, North Dakota, Utah, and Wyoming, and selected regions of Arizona, Nebraska, Nevada, Oregon, South Dakota and Washington. The 2004 limits are the same as for the basic program, except there also is a 150 ppm maximum refinery annual average. For 2005, the refinery annual average remains at 150 ppm maximum while the corporate pool annual average per gallon cap are the same as the basic program. If more than 50% of a refiner’s gasoline is GPA in 2004 or 2005, the corporate pool average does not apply in 2004-2005. For 2006, the corporate pool annual average is eliminated while the other limits remain the same for 2005. For 2007, the limits become the same as for the basic program with the refinery annual average at 30 ppm maximum and the per gallon cap at 80 ppm. The downstream enforcement level is at 95 ppm maximum (80 ppm refinery cap plus 15 ppm reproducibility tolerance). However, there is a process to obtain a two-year extension (through 2007 and 2008) of the 2006 limits where the GPA refinery agrees to also produce 15 ppm maximum sulfur diesel fuel beginning in 2006.

X3.6.3 For refineries that qualify for small refiner status, another set of sulfur limits apply for the period 2004 through 2007. The annual average sulfur level standard for each refinery is determined based on the refinery’s 1997-1998 sulfur level baseline and the maximum ranges from 30 ppm to 300 ppm. The sulfur cap is similarly based and can range from 30 ppm to 450 ppm. Small refineries may also obtain a three-year extension (through 2008, 2009, and 2010) of the 2007 limits where the small refiner agrees to produce 15 ppm maximum sulfur diesel fuel beginning in 2006.

**X4. METHOD FOR CALCULATING MASS PERCENT OXYGEN OF GASOLINE-OXYGENATE BLENDS**

**X4.1 Scope**

X4.1.1 Test Method D 4815 provides a procedure for calculating the mass oxygen content of fuels using oxygenate concentration in mass percent. When oxygenate concentration in mass percent is not available, the oxygen concentration of these fuels can be determined indirectly by: (1) measuring the volume concentration of the oxygenates in the blend, which may be reported from Test Method D 4815 or equivalent test method, (2) measuring the density or relative density of the blend, (3) converting the oxygenate concentrations from volume to mass concentrations, and (4) converting the mass oxygenate concentrations to mass oxygen concentrations using the oxygen mass fractions of the oxygenates present.

**X4.2 Procedure**

X4.2.1 The following steps are used to determine the total mass oxygen concentration of gasoline-oxygenate blends when indirect calculation is necessary.

**X4.2.1.1** Determine the volume concentrations of oxygenates in a gasoline-oxygenate blend (Test Method D 4815 or equivalent test method).

**X4.2.1.2** Determine the density or relative density of the gasoline-oxygenate blend (Test Methods D 287, D 1298, or D 4052).

**X4.2.1.3** The oxygen mass percent of the gasoline-oxygenate blend is calculated using the following general equation. The densities or relative densities and oxygen mass fractions of a number of pure oxygenates are provided in Table X4.1 for use in Eq X4.1. The choice of density or relative density must be the same as determined in X4.2.1.2 for the gasoline-oxygenate blend.

\[
\text{Oxygen, Mass \%} = \frac{V_1 \times d_1 \times O_1 + V_2 \times d_2 \times O_2 + \ldots + V_n \times d_n \times O_n}{V_0 \times d_0} \times 100
\]

(X4.1)
TABLE X4.1 Densities, Relative Densities, and Oxygen Mass Fractions of Pure Oxygenates

<table>
<thead>
<tr>
<th>Oxygenate</th>
<th>Density, g/ml</th>
<th>Relative Density 15.0/15.5°C</th>
<th>Oxygen Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl Alcohol</td>
<td>0.7913</td>
<td>0.7963</td>
<td>0.4993</td>
</tr>
<tr>
<td>Ethyl Alcohol</td>
<td>0.7894</td>
<td>0.7930</td>
<td>0.3473</td>
</tr>
<tr>
<td>n-Propyl Alcohol</td>
<td>0.8038</td>
<td>0.8090</td>
<td>0.2662</td>
</tr>
<tr>
<td>iso-Propyl Alcohol</td>
<td>0.7855</td>
<td>0.7899</td>
<td>0.2662</td>
</tr>
<tr>
<td>n-Butyl Alcohol</td>
<td>0.8097</td>
<td>0.8137</td>
<td>0.2106</td>
</tr>
<tr>
<td>iso-Butyl Alcohol</td>
<td>0.8016</td>
<td>0.8058</td>
<td>0.2158</td>
</tr>
<tr>
<td>sec-Butyl Alcohol</td>
<td>0.8056</td>
<td>0.8114</td>
<td>0.2158</td>
</tr>
<tr>
<td>tertiary-Butyl Alcohol</td>
<td>0.7866</td>
<td>0.7922</td>
<td>0.2158</td>
</tr>
<tr>
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* Extrapolated, below freezing temperature.

X4.3 Example Calculation

X4.3.1 Assume that a gasoline-oxygenate blend is reported to contain 9.5 volume % ethanol and 2.0 volume % methyl tertiary-butyl ether and that the relative density of the blend is measured to be 0.7450, 15.0/15.5°C (60/60°F).

X4.3.2 Using the relative density and oxygen mass fraction data for ethanol and methyl tertiary-butyl ether from Table X4.1, the following mass % oxygen is calculated for this gasoline-oxygenate blend.

\[
\text{Oxygen, Mass %} = \left( \frac{9.5 \times 0.7939 	imes 0.3473 + 2.0 \times 0.7450 	imes 0.1815}{100} \right) \times 100 = 388
\]

X4.4 Precision

X4.4.1 The precision of this calculation method is a function of the individual precisions of density or relative density (Test Methods D 287, D 1298, or D 4052) and oxygenate analysis (Test Method D 4815 or equivalent). Because the repeatability and reproducibility vary with the analyses used, no estimate is provided.

X5. MICROBIAL CONTAMINATION

X5.1 Uncontrolled microbial contamination in fuel systems may cause or contribute to a variety of problems including increased corrosivity, and decreased stability, filterability, and caloric value. Microbial processes in fuel systems may also cause or contribute to system damage.

X5.2 Because the microbes contributing to the aforementioned problems may not be present in the fuel itself, no microbial quality criterion for fuels is recommended. However, it is important that personnel responsible for fuel quality understand how uncontrolled microbial contamination may affect fuel quality.

X5.3 Guide D 6469 provides personnel with limited microbiological background an understanding of the symptoms, occurrences, and consequences of chronic microbial contamination. Guide D 6469 also suggests means for detecting and controlling microbial contamination in fuels and fuel systems.

X6. FUEL FILTRATION

X6.1 During the distribution of spark-ignition fuels, it is possible for them to become contaminated with potential filter blocking materials. While proper handling will minimize the contamination levels, it is recommended that all fuel dispensers be equipped with filters of 10 μm or less nominal pore size at point of delivery to the customer.

X7. OPTIONAL USEFUL EQUIPMENT FOR SILVER STRIP TEST

X7.1 Viewing Tube

X7.1.1 A useful flat glass test tube for holding tarnished silver strips for inspection or for storage for later inspection is illustrated and dimensioned in Fig. X7.1.

X7.2 Strip Vise

X7.2.1 A useful and convenient vise for holding up to four silver strips during final polishing is illustrated and dimensioned in Fig. X7.2.
**FIG. X7.1 Flat Glass Viewing Test Tube**

Notes:
1. Dimensions in millimetres.
2. The dimensions are the minimum dimensions that allow the introduction of a silver strip.
3. The tube is to be free of air inclusions or similar defects.
X8. WATER TOLERANCE OF ETHANOL BLENDS

X8.1 Water tolerance is the ability of a fuel to dissolve water without phase separation. It is not of concern for gasoline because of the very low solubility of water in hydrocarbons. Water tolerance is of some concern with gasoline-ether blends because of the limited solubility of ethers in water, but it is of great concern for gasoline-alcohol blends because of the very high solubility of alcohols in water. Blends of gasoline with low-molecular weight alcohols generally will dissolve about 0.1 to 0.7 mass percent of water under normal conditions, depending on the nature and amount of the alcohol(s) used, the specific hydrocarbons present, and the temperature of the blend. When blends are exposed to a greater amount of water than they can dissolve, they separate into a lower, alcohol-rich aqueous phase, the volume of which can be significantly greater than that of the additional water, and an upper alcohol-poor hydrocarbon phase. As the lower aqueous phase can be highly corrosive to many metals and the engine cannot operate on it, such separation is very undesirable. Similarly, the upper hydrocarbon phase may no longer meet needed volatility and anti-knock properties. Blends containing low-molecular weight alcohols are generally hygroscopic and can eventually absorb enough moisture from ambient air to cause separation. The problem of phase separation can usually be avoided if the fuels are sufficiently water-free initially and care is taken during distribution to prevent contact with water. Gasoline-alcohol blends should be resistant to phase separation at the lowest temperatures to which they are likely to be subjected, dependent on the time and place of their intended use, as indicated in Table X8.1. The values in Table X8.1 are the 10th percentile 6-h minimum temperatures, with each reading specifically defined as the highest temperature of the six coldest consecutive hourly temperature readings of a 24-h day. For April through September (and occasionally October, and year-round for Hawaii), Table X8.1 specifies a minimum phase separation temperature of 10°C (50°F), even though the 10th percentile 6-h minimum temperature can be higher. Use of this temperature limit also reduces the risk of separation of the fuel in storage tanks where temperatures may be lower than ambient.

Note X8.1—The values in Table X8.1 are taken from the U.S. Army Belvoir Research Development and Engineering Center’s Report No. 316, entitled, “A Predictive Study for Defining Limiting Temperatures and Their Application in Petroleum Product Specifications.” This can be obtained as Publication AD756-420 from the National Technical Information Service in Springfield, VA 22151.

X8.2 The most important factor, besides the quantity of water contacted, which governs the water tolerance of a fuel, is its temperature. As the temperature of the blend decreases, water tolerance decreases. Table X8.1 indicates the lowest temperatures to which a blend is likely to be subjected, dependent on the time and place of its intended use. Some other factors that affect water tolerance are alcohol concentration and aromatics content of the fuel. Water tolerance is improved as both alcohol and aromatics contents increase.

X8.3 With some gasoline-oxygenate blends, formation of a haze may occur when filling a storage tank that contains water bottoms, while congealing of gasoline-oxygenate blends with gasoline, or when a sufficient decrease in temperature occurs. However, the haze may not be stable and the fuel will clear usually in a short period of time.

X8.4 A more critical water tolerance concern is the potential increase in storage tank water bottoms. This can occur when some gasoline-oxygenate blends and gasoline-alcohol blends in particular are added to a tank that contains sufficient water to extract some or all of the oxygenate component from the fuel.
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SUMMARY OF CHANGES

Subcommittee D02.A0.01 has identified the location of selected changes to this standard since the last issue (D 4814-08b) that may impact the use of this standard. (Approved Jan. 15, 2009.)

1. Added wording to Footnote A and added Footnotes G and H in Table 1.

2. Deleted wording from Footnote D in Table 2.

3. Updated Louisiana information in Table 5 and Table 6.

Subcommittee D02.A0.01 has identified the location of selected changes to this standard since the last issue (D 4814-08a) that may impact the use of this standard. (Approved Sept. 1, 2008.)

1. Modified 5.2.4, X1.1.1, X2.1.1, X2.1.2, X2.1.4, X2.2.2.4, X2.3.2, and X2.4.1.

2. Added new research report.

Subcommittee D02.A0.01 has identified the location of selected changes to this standard since the last issue (D 4814-08) that may impact the use of this standard. (Approved Aug. 1, 2008.)

1. Revised Footnote D in Table 2.

Subcommittee D02.A0.01 has identified the location of selected changes to this standard since the last issue (D 4814-07b) that may impact the use of this standard. (Approved July 1, 2008.)

1. Added X1.12.5 and Eq X1.2 with accompanying figures and any references in related text.

2. Removed Nomogram method from Appendix X2, along with accompanying figures and any references in related text.
Subcommittee D02.A0.01 has identified the location of selected changes to this standard since the last issue (D 4814–07a) that may impact the use of this standard. (Approved Dec. 1, 2007.)

1. Revised 1.7.
2. Deleted decimal points and added footnotes to Table 1.
3. Revised Footnote D in Table 2.

Subcommittee D02.A0.01 has identified the location of selected changes to this standard since the last issue (D 4814–07) that may impact the use of this standard. (Approved July 15, 2007.)

1. Removed Test Method D 2533 from the Referenced Documents, 5.2.4, 7.1.2, X1.10, X2.1, and X2.4 and revised text as necessary to refer to Test Method D 5188.
2. Removed Footnote E on water tolerance from Table 2.
3. Revised format of Table 3.
4. Removed withdrawn Test Method D 6422 from the Referenced Documents, 5.7.1, and 7.1.10.
5. Revised 5.7.1.
6. Removed X1.17 and added Appendix X8 to discuss water tolerance issues.
7. Changed original Table 13 to Table X3.1.
8. Upated Michigan SIP requirement in Table 12.
9. Corrected reference to footnote in Table 4 for Delaware.

Subcommittee D02.A0.01 has identified the location of selected changes to this standard since the last issue (D 4814–06a) that may impact the use of this standard. (Approved April 15, 2007.)

1. Deleted Note X3.1.

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Standard Specification for
Grade 82 Unleaded Aviation Gasoline

This standard is issued under the fixed designation D 6227; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers Grade 82 unleaded aviation gasoline, which is defined by this specification as for use only in engines and associated aircraft that are specifically approved by the engine and aircraft manufacturers, and certified by the National Certifying Agencies to use this fuel. This fuel is not considered suitable for use in other engines and associated aircraft that are certified to use aviation gasoline meeting Specification D 910.

1.2 A fuel may be certified to meet this specification by a producer as Grade 82 UL aviation gasoline only if blended from component(s) approved for use in Grade 82 UL aviation gasoline by the refiner(s) of such components, because only the refiner(s) can attest to the component source and processing, absence of contamination, and the additives used and their concentrations. Consequently, re-classifying of any other product to Grade 82 UL aviation gasoline does not meet this specification.

1.3 Appendix X1 contains an explanation for the rationale of the specification. Appendix X2 details the reasons for the individual specification requirements.

1.4 The values stated in SI units are to be regarded as the standard. The values given in parentheses are provided for information only.

2. Referenced Documents

2.1 ASTM Standards:

D 86 Test Method for Distillation of Petroleum Products at Atmospheric Pressure
D 130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test
D 357 Method of Test for Knock Characteristics of Motor Fuels Below 100 Octane Number by the Motor Method

D 381 Test Method for Gum Content in Fuels by Jet Evaporation
D 873 Test Method for Oxidation Stability of Aviation Fuels (Potential Residue Method)
D 909 Test Method for Knock Characteristics of Aviation Gasolines by the Supercharge Method
D 910 Specification for Aviation Gasolines
D 1266 Test Method for Sulfur in Petroleum Products (Lamp Method)
D 2386 Test Method for Freezing Point of Aviation Fuels
D 2392 Test Method for Color of Dyed Aviation Gasolines
D 2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry
D 2700 Test Method for Motor Octane Number of Spark-Ignition Engine Fuel
D 3120 Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry
D 3231 Test Method for Phosphorus in Gasoline
D 3237 Test Method for Lead in Gasoline by Atomic Absorption Spectroscopy
D 3338 Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
D 4087 Practice for Manual Sampling of Petroleum and Petroleum Products
D 4171 Specification for Fuel System Icing Inhibitors
D 4529 Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
D 4809 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)
D 4815 Test Method for Determination of MTBE, ETBE, TAME, DIPE, tertiary-1,1-Diethylethanol and C8 to C10 alcohols in Gasoline by Gas Chromatography
D 4953 Test Method for Vapor Pressure of Gasoline and Gasoline-Oxyylene Blends (Dry Method)
D 5059 Test Methods for Lead in Gasoline by X-Ray Spectroscopy
D 5190 Test Method for Vapor Pressure of Petroleum Products (Automatic Method)

A Summary of Changes section appears at the end of this standard.
D 5191 Test Method for Vapor Pressure of Petroleum Products (Mini Method)
D 5433 Test Method for Determination of Total Sulfur in Light Hydrocarbons, Motor Fuels and Oils by Ultraviolet Fluorescence
D 5482 Test Method for Vapor Pressure of Petroleum Products (Mini Method-Atmospheric)
D 5590 Test Method for Determination of Oxygenates in Gasoline by Gas Chromatography and Oxygen Selective Flame Ionization Detection
D 5845 Test Method for Determination of MTBE, ETBE, TAME, DIPE, Methanol, Ethanol and tert-Butanol in Gasoline by Infrared Spectroscopy
D 5983 Specification for Methyl tertiary-Butyl Ether (MTBE) for Downstream Blending for Use in Automotive Spark Ignition Engine Fuel
D 6469 Guide for Microbial Contamination in Fuels and Fuel Systems
E 29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
2.2 Military Standard
MIL-PRF-25017F Performance Specification for Inhibitor, Corrosion/Lubricity Improver, Fuel Soluble
QPL-25017 Qualified Products List of Products Qualified Under Performance Specification MIL-PRF-25017F

3. Terminology
3.1 Definitions:
3.1.1 aviation gasoline, n—gasoline possessing specific properties suitable for fueling aircraft powered by reciprocating spark ignition engines.
3.1.1.1 Discussion—The principal properties of aviation gasoline include volatility limits, stability, detonation-free performance in the engine for which it is intended, and suitability for low temperature performance.

4. Grades
4.1 The specification covers one grade of unleaded aviation gasoline designated Grade 82 UL. Grade 82 UL is the only aviation gasoline defined by this specification and the grade shows the minimum motor octane rating.

5. General
5.1 This specification, unless otherwise provided, prescribes the required properties of unleaded aviation gasoline at the time and place of delivery.

6. Material
6.1 Aviation gasoline, except as otherwise specified in this specification, shall consist of blends of refined hydrocarbons derived from crude petroleum, natural gasoline or blends, thereof, with specific aliphatic ethers, synthetic hydrocarbons, or aromatic hydrocarbons. When applicable, methyl tertiary-butyl ether (MTBE) shall conform to the requirements of Specification D 5983. Types and quantities of trace alcohols shall meet the requirements of Table I and 6.2.4.2.
6.2 Only additives approved by this specification are permitted. In addition to identification dyes, corrosion inhibitors, antioxidants, and metal deactivators, fuel system icing inhibitor additives are permitted under 6.2.4. Permitted additives may be added to aviation gasoline in the amount of and to the composition specified in the following list of approved materials. The quantities and types shall be declared by the manufacturer. Additives added after the point of manufacture shall also be declared.
6.2.1 Antioxidants—The following oxidation inhibitors may be added to the gasoline separately or in combination in total concentration not to exceed 12 mg of inhibitor (not including weight of solvent) per litre of fuel.
6.2.1.1 2,6-ditertiary-butyl-phenol.
6.2.1.2 2,6-ditertiary-butyl-4-methyl-phenol.
6.2.1.3 2,4-dimethyl-6-tertiary-butyl-phenol.
6.2.1.4 2,6-ditertiary-butyl-phenol, 75 % minimum.
Tertiary and tert-tertiary-butyl-phenols, 25 % maximum.
6.2.1.5 2,4-dimethyl-6-tertiary-butyl-phenol, 55 % minimum; 4-methyl-2,6-ditertiary-butyl phenol 15 % minimum; the remainder as a mixture of monomethyl and dimethyl-tertiary-butyl-phenols.
6.2.1.6 2,4-dimethyl-6-tertiary-butyl-phenol, 72 % minimum.
Mixture of tertiary-butyl-methyl-phenols and tertiary-butyl-dimethyl-phenols, 28 % maximum.
6.2.1.7 2,6-ditertiary-butyl-4-methyl-phenol, 35 % minimum.
Mixed methyl, ethyl, and dimethyl tertiary-butyl-phenols, 65 % maximum.
6.2.1.8 2,4-d-tertiary-butyl-phenol, 60 % minimum.
Mixed tertiary-butyl-phenol, 40 % maximum.
6.2.1.9 Butylated ethyl-phenols, 55 % minimum;
Butylated methyl and dimethyl-phenols, 45 % maximum.
6.2.1.10 Mixture of a di- and tri-isopropyl-phenols, 75 % minimum.
Mixture of di- and tri-tertiary-butyl-phenols, 25 % maximum.
6.2.1.11 NN' di-secondary butyl-para phenylene diamine.
6.2.1.12 NN' di-isopropyl-para-phenylene-diamine.
6.2.1.13 N-secondary butyl, NN'-phenyl ortho-phenylenediamine.
6.2.2 Metal Deactivators—A metal deactivator, N,N'-disalicylidene-1,2-propane diamine may be added to the gasoline in an amount not to exceed 3.0 mg/l.
6.2.3 Corrosion Inhibitors—Corrosion inhibitors that conform to MIL-PRF-25017F may be added to the gasoline in amounts not exceeding the maximum allowable concentrations listed in the latest revision of QPL-25017.
6.2.4 Fuel System Icing Inhibitor
6.2.4.1 Diethylene glycol nonomethyl ether, conforming to the requirements of Specification D 4171 (Type II), may be used in concentrations of 0.10 to 0.15 volume %.
### TABLE 1 Requirements for Grade 82 UL Aviation Gasoline

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<th>Property</th>
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<td>Motor method octane number, min</td>
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<tr>
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<td>Distillation temperature, °C (°F) at % evaporated</td>
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<td>16 volume %, max</td>
<td>66 (166)–121 (250)</td>
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<td>55 volume %, max</td>
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<td>Evp point, max</td>
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<td>Residue, volume % max</td>
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<td>Distillation loss, volume %, max</td>
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<td>Net heat of combustion, min MJ/kg (BTU/lb)</td>
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<td>Freezing point, °C (°F), max</td>
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<td>Vapor pressure, kPa (psig), max</td>
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<td>kPa (psig), min</td>
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<td>Lead content, g/l (g/L, gal), max</td>
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<td>Copper strip corrosion, 3 h at 55°C (122°F), max</td>
<td>0.07</td>
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<td>Sulfur, mass %, max</td>
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<td>Potential gum (5-h aging), max, mg/100mL</td>
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<td>Alcohol and other contaminant, max</td>
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<td>Combined aliphatic ethers, methanol, and ethanol, as mass % oxygen, max</td>
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6.2.4.2 Isopropyl alcohol conforming to the requirements of Specification D 4171 (Type II) may be used in concentrations recommended by the aircraft manufacturers when required by the aircraft owner or operator.

7. Detailed Requirements

7.1 The aviation gasoline shall conform to the requirements in Table 1.

8. Workmanship

8.1 The finished fuel shall be visually free of water, sediment, and suspended matter.

Note 1—See Practice D 4057 for appropriate sampling procedures.

9. Reports

9.1 The type and number of reports to ensure conformance with the requirements of this specification shall be mutually agreed to by the purchaser and the supplier of the aviation gasoline.

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10. Test Methods

10.1 The requirements enumerated in this specification shall be determined in accordance with the following ASTM test methods:

10.1.1 Motor Octane—Test Method D 2700.

10.1.2 Color—Test Method D 2392.

10.1.3 Distillation—Test Method D 86.

10.1.4 Net Heat of Combustion—Test Method D 3338, D 4529, or D 4809.

10.1.5 Freezing Point—Test Method D 2866.

10.1.6 Vapor Pressure—Test Method D 4953, D 5190, or D 6582.

10.1.7 Lead Content—Test Method D 3237 or D 5059 (Test Method C).

10.1.8 Copper Strip Corrosion—Test Method D 130 (3 h at 50°C (122°F)).

10.1.9 Sulfur—Test Method D 1266, D 2622, D 3120, D 4294, or D 5453.

10.1.10 Potential Gum—Test Method D 873, except that wherever the letter X occurs (referring to oxidation time),
insert the number 5, designating the number of hours prescribed in this specification.

10.1.11 Alcohols/Ethers Detection—Test Method D 4815,
D 5599, or D 5845.

APPENDIXES
(Nonmandatory Information)

XI. REASONS FOR SPECIFICATION

X1.1 Introduction—Aviation gasoline defined by this specification is for use only in engines and associated aircraft specifically designed to operate on Grade 82 UL defined by this specification.

X1.2 To ensure ready identification of fuel meeting this specification, it is dyed purple.

X2. SIGNIFICANT FACTORS FOR UNLEADED AVIATION GASOLINE

X2.1 Introduction

X2.1.1 This specification was developed to identify broad distillation range refinery products, including refined hydrocarbons derived from crude petroleum, or blends thereof, with synthetic hydrocarbons and specific aliphatic ether blends, suitable for low octane unleaded aviation gasoline applications. The requirements of Table 1 are quality limits established on the basis of development and certification tests performed on airframes and engines specifically designed to use these fuels.

X2.1.2 Engines certified for low octane fuels and their associated aircraft operate within a variety of mechanical, physical, and chemical environments. The properties of unleaded aviation gasoline (Table 1) must be properly balanced to give satisfactory engine performance over a wide range of conditions.

X2.2 Antiknock Quality

X2.2.1 The fuel-air mixture in the cylinder of a spark-ignition engine will, under certain conditions, spontaneously ignite ahead of the flame front. This will cause a knock, which is usually inaudible in aircraft engines. This knock, if permitted to continue, may result in serious loss of power and damage to the aircraft engine.

X2.2.2 Traditional leaded aviation gasolines have been defined by both lean and rich mixture ratings. A minimum lean mixture rating of 82.0 determined by the motor method (Test Method D 2700) provides satisfactory antiknock properties on engines certified for low octane fuels. Rich mixture ratings by Test Method D 909 were developed for older large displacement, high output engines for which this fuel is not suitable.

X2.2.3 The motor Test Method D 2700 is an engine method for determining the knock characteristics at a lean fuel-air ratio of fuels for use in spark-ignition engines. It was originally developed as Test Method D 357 to test motor gasolines for motor octane number, but an extensive program revealed that the octane number rating of current aviation gasolines could also be determined by the motor method. Knock characteristics of a test fuel are established by comparing its knocking tendency with those for blends of ASTM reference fuels of known octane number under prescribed operating conditions.

X2.3 Fuel Metering and Vaporization—General Comments

X2.3.1 In most spark-ignition engines, the aviation gasoline is metered in liquid form through carburetors or low pressure injectors. Fuel vaporization starts in the carburetor or downstream of the injector and continues in the intake manifold from which the fuel-air enters the cylinders of the engine. The volatility, the tendency to evaporate or change from a liquid to a gaseous state, is an extremely important characteristic of aviation fuel.

X2.3.2 Gasolines that vaporize too readily may boil in fuel lines or in fuel metering devices, particularly at altitude increases, and cause vapor lock with resultant power loss. Conversely, fuels that do not completely vaporize may cause engine malfunctioning of other sorts. Therefore, a proper
X2.4 Volatility

X2.4.1 Vapor Pressure—The vapor pressure of an aviation gasoline is the measure of the tendency of the more volatile components to evaporate. Fuels having a vapor pressure no higher than 93 kPa (135 psi) will be free of vapor-locking tendencies under operating conditions of the aircraft developed for such fuels. The minimum vapor pressure of 38 kPa (5.5 psi) adopted in this specification is consistent with the requirements of other aviation gasolines.

X2.4.2 Distillation—Gasoline is made up of a broad range of hydrocarbon components. Distillation temperatures are a measure of a fuel’s volatility. The method of measuring distillation temperatures is useful in comparing fuels, but is not intended to separate or identify quantitatively the individual hydrocarbons present.

X2.4.2.1 A maximum value is set on the 30 % evaporated point to ensure ease of starting and a reasonable degree of flexibility during the warm-up period.

X2.4.2.2 To guard against too high a volatility, which might lead to carburetor icing or vapor lock, or both, (also protected against by the vapor pressure), a minimum value is set for the 50 % evaporated points.

X2.4.2.3 A maximum value is specified for the 50 % evaporated temperature to ensure average volatility sufficient to permit adequate evaporation of the fuel in the engine induction system. Insufficient evaporation may lead to loss of power.

X2.4.2.4 A maximum temperature is prescribed for the 90 % evaporated point to prevent too much liquid fuel being delivered to the cylinders, resulting in power loss, and to prevent poor distribution to the various cylinders. Such a condition might lead to engine roughness, perhaps accompanied by knocking and damage to the engine. Excessive dilution of the lubricating oil may result from too high a 90 % evaporated point.

X2.4.2.5 A maximum is placed on the final boiling point (end point), which together with the maximum prescribed for the 90 % evaporated point, is used to prevent incorporation of excessively high boiling components in the fuel, which may lead to mal-distribution, spark plug fouling, power loss, and lubricating oil dilution.

X2.4.2.6 A maximum value is specified for the distillation residue to prevent the inclusion of undesirable high-boiling components essentially impossible to burn in the chamber. The presence of such residue may reflect the degree of care with which the product is refined or handled. The amount of residue, along with the end-point temperature, can be used as an indication of contamination with high-boiling materials.

X2.4.2.7 The stipulation of a minimum recovery and a maximum loss in this specification is conjunction with the vapor pressure requirement is intended to protect against excessive losses by evaporation in storage, handling, and in the aircraft tank. It is also a check on the distillation test technique.

X2.5 Corrosion of Fuel System and Engine Parts

X2.5.1 Copper Strip—The requirement that aviation gasoline must pass the copper strip corrosion test provides assurance that copper components of the fuel system will not be corroded by sulfur compounds in the fuel.

X2.5.2 Sulfur—Total sulfur content of aviation fuels is significant because the products of combustion of sulfur can cause corrosive wear of engine parts.

X2.6 Low Temperature Performance

X2.6.1 Fuel System Ice Inhibitor—Diethylene glycol monomethyl ether, approved in 6.2.4.1, and isopropyl alcohol, approved in 6.2.4.2, shall be in accordance with the requirements shown in Specification D4171.

X2.6.2 Fuel Freezing Point—A freezing point requirement is specified to preclude solidification of any of the materials cited in 6.1 and 6.2 at extremely low temperatures with the consequent interference with fuel flow to the engine.

X2.7 Heat of Combustion

X2.7.1 The net heat of combustion provides a knowledge of the amount of energy obtainable from a given fuel for the performance of useful work. In this instance, power. Aircraft design and operation are dependent upon the availability of a certain predetermined minimum amount of energy as heat. Consequently, reductions in heat energy are accompanied by an increase in fuel consumption with corresponding loss of range. Therefore, a minimum net heat of combustion requirement is incorporated in the specification.

X2.7.2 The calculation method presented here provides a correction for oxygen content when Test Methods D3338 and D4529 are adopted to determine the net heat of combustion of oxygenated blends.

\[
Q = \frac{W_1 (Q_{P1}) + W_2 (Q_{P2}) + W_3 (Q_{P3}) + W_4 (Q_{P4}) + W_5 (Q_{P5})}{W_1 + W_2 + W_3 + W_4 + W_5} \quad (X.2.1)
\]

where:

- \(Q\) = net heat of combustion, MJ/kg (BTU/lb) of the gasoline - ether blend,
- \(W_1\) = oxygenate-free hydrocarbon mass fraction (or mass \(\%\) \(\div\) 100),
- \(Q_{P1}\) = net heat of combustion, MJ/kg (BTU/lb) of oxygenate-free hydrocarbon fraction, calculated from measured properties of the fuel,
- \(W_2\) = MTBE mass fraction (or mass \(\%\) \(\div\) 100),
- \(Q_{P2}\) = net heat of combustion of MTBE listed in the research report, which is 35.12 MJ/kg (15 100 BTU/lb),
- \(W_3\) = TAME mass fraction (or mass \(\%\) \(\div\) 100),
- \(Q_{P3}\) = net heat of combustion of TAME listed in the research report, which is 36.49 MJ/kg (15 690 BTU/lb),
- \(W_4\) = ETBE mass fraction (or mass \(\%\) \(\div\) 100),
- \(Q_{P4}\) = net heat of combustion of ETBE listed in the research report, which is 36.36 MJ/kg (15 635 BTU/lb),
- \(W_5\) = DIPE mass fraction (or mass \(\%\) \(\div\) 100), and
- \(Q_{P5}\) = net heat of combustion of DIPE listed in the research report, which is 38.13 MJ/kg (16 593 BTU/lb).
and where:

\[ W_1 + W_2 + W_3 + W_4 + W_5 = 1 \]

X2.7.3 If the properties of the oxygenate-free hydrocarbon fraction of the fuel are not known or if only the gasoline-ether blend properties are available, it is not possible to calculate the net heat of combustion of the gasoline-ether blend using Test Method D 3338 or D 4529. Under these circumstances, the net heat of combustion should be measured using Test Method D 4809. See SAE J1498, for further discussion.

X2.7.4 The research report establishes the practical minimum value of net heat of combustion of 40.8 MJ/kg (17.5 kcal/lb) adopted in this specification. However, the value includes the maximum anticipated ether concentrations, and in most cases, actual net heating values will exceed this minimum.

X2.8 Oxygenates

X2.8.1 Oxygenates are oxygen-containing, ashless compounds, such as alcohols and ethers, which can be used as a fuel supplement.

X2.8.2 Aliphatic ethers allowed up to the specification limit include methyl tertiary-butyl ether (MTBE), tertiary-amy1 methyl ether (TAME), ethyl tertiary-butyl ether (ETBE), and diisopropyl ether (DIPE).

X2.8.3 The deliberate addition of alcohols is prohibited by this specification, except that isopropyl alcohol is allowed as a fuel system icing inhibitor field additive (see 6.2.4.2) and is limited by aircraft manufacturers to a maximum concentration of 1.0 volume %. Alcohols are prohibited because of their excessive water solubility, increase in vapor pressure, material incompatibility, and in addition for methanol, corrosivity. Low concentrations of methanol and ethanol are only permitted by this specification because they are unreacted components from the manufacturing of aliphatic ethers. The total of the combination of methanol and ethanol shall not exceed 0.3 mass % oxygenate as determined by Test Method D 4615, D 5599, or D 5845.

X2.9 Fuel Cleanliness, Handling, and Storage Stability

X2.9.1 Existent Gum—The amount of non-volatile residue remaining after evaporation by a high temperature air jet. This residue may represent solid or heavy liquid contaminants or insoluble residue formed by oxidation in storage.

X2.9.2 Potential Gum—Fuel must be usable after storage for variable periods under a variety of climatic conditions. The potential gum test, which is an accelerated oxidation method, is used to estimate fuel stability in storage and the effectiveness of oxidation inhibitors. If the fuel is to be stored under relatively mild conditions for short periods, an oxidation period of 5 h is generally considered sufficient to indicate if the desired stability has been obtained.

X2.9.3 Dyes—Colors are used in aviation fuels to differentiate between grades. Service experience has indicated that only certain dyes and only certain amounts of dye can be tolerated without manifestation of induction system deposition.

The composition of the approved dyes as well as the maximum quantity of each permissible dye is specified in Table 1. The allowable color levels are established by Test Method D 2939. The color purple was selected for this grade because the former purple grade, Grade 115/145, has been removed from Specification D 910 and is no longer widely available.

X2.9.4 Microbial Contamination—Uncontrolled microbial contamination in fuel systems may cause or contribute to a variety of problems including corrosion, odor, filter plugging, decreased stability and deterioration of fuel/water separation characteristics. In addition to system component damage, off-specification fuel can result.

X2.9.5 Guide D 4690 provides personnel with limited microbiological background an understanding of the systems, occurrence, and consequences of chronic microbial contamination. The guide also suggests means for detection and control. Biocides used in aviation fuels must follow engine and airframe manufacturers’ approval guidelines.

X2.10 Miscellaneous

X2.10.1 Lead Content—A number of analytical test methods are permitted to cover the unintentional presence of lead in unleaded fuel. The intentional addition of lead or phosphorus compounds to unleaded fuel is not permitted. Industry practice currently limits maximum concentrations to 0.013 g of lead/L (0.05 g/U.S. gal) and 0.0013 g of phosphorus/L (0.005 g/U.S. gal) (see Test Method D 3231), respectively.

X2.10.2 Aromatic Content—Low boiling aromatics, which are common constituents of aviation gasolines, are known to affect elastomers to a greater extent than other components.
186

SUMMARY OF CHANGES

Subcommittee D02.10 has identified the location of selected changes to this standard since the last issue (D 6227-04) that may impact the use of this standard. (Approved Nov. 1, 2004)

1) Added sentence to the end of 6.2.

Subcommittee D02.10 has identified the location of selected changes to this standard since the last issue (D 6227-00) that may impact the use of this standard. (Approved June 1, 2004)

1) Added sentence to the end of 6.2.

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service bulletin

January 1977

Distributors, Dealers, Engine Overhaul Facilities, Owners and Operators of Teledyne Continental Motors' Aircraft Engines

USE OF ALTERNATE AVIATION GRADE FUELS IN ENGINES ORIGINALLY CERTIFICATED ON 80/8791/96 and 100/130 GRADE FUELS

Gentlemen:

Numerous customer inquiries have been received regarding the use of alternate fuels in TCM engines. The limited availability of 80/87 octane fuel has demanded increased utilization of higher grade fuels.

The American Society for Testing and Materials (ASTM) has recently revised ASTM D910-70, the standard Specification for Aviation Fuels. The new specification, D910-75, re-identifies the three current grades of aviation fuel as Grade 80, Grade 100, and Grade 100LL (low lead). The three grades replace those fuels commonly known as Grade 80/87 and Grade 100/130.

Although Grade 100 and 100LL have the same anti-knock qualities, they differ in the maximum allowable tetroxylllead content.

The following table provides a comparison of the current and previous fuel specifications:

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM D910-70</td>
</tr>
<tr>
<td>GRADE</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>80/87</td>
</tr>
<tr>
<td>91/96</td>
</tr>
<tr>
<td>100/130</td>
</tr>
<tr>
<td>115/145</td>
</tr>
</tbody>
</table>

The amount of tetroxylllead in these higher grade fuels has increased the lead build up and fouling of Spark plugs along with valve erosion incidents reported on some lower compression engines.
Those TCM engines most affected include the A65, A75, C-75, C-85, C-90, C125, C-145, O-200, O-300 and GO-300 series.

The following list of replacement components, by engine series, improves engine reliability when operating on the higher grade alternate fuels. Refer to Service Bulletin M76-8.

<table>
<thead>
<tr>
<th>ENGINE MODEL</th>
<th>COMPONENT</th>
<th>PART NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>A65 and A75</td>
<td>Intake Valve</td>
<td>639661</td>
</tr>
<tr>
<td></td>
<td>Exhaust Valve</td>
<td>639662</td>
</tr>
<tr>
<td>Go-300</td>
<td>Exhaust Valve</td>
<td>631639</td>
</tr>
<tr>
<td></td>
<td>Intake Valve</td>
<td>641792</td>
</tr>
<tr>
<td></td>
<td>Intake Valve Seat</td>
<td>641793</td>
</tr>
<tr>
<td>C75, C85, C90, O-1000, O-300, C-125, C-145</td>
<td>Intake Valve</td>
<td>641792</td>
</tr>
<tr>
<td></td>
<td>Intake Valve</td>
<td>641793</td>
</tr>
</tbody>
</table>

The valves and valve seat inserts installed in TCM engines F-165, E-185, E-225, O-470, 10-470-I and 10-470-K series engines are compatible with higher grade fuels. These engines were originally certified on 80/87 octane fuel, however, field service history indicates that operation on Grade 100LL does not adversely affect intake or exhaust valve longevity.

**SPARK PLUG LEAD FOULING**

Spark plug lead fouling increases when higher leaded fuels are used in engines originally certified on 80/87 octane fuel. Such fouling can be reduced by more frequent spark plug cleaning and spark plug rotation. Fine wire spark plugs that are FAA approved for use in those TCM engines listed may further alleviate fouling problems. In any case, the rotation of plugs every 50 hours of operation and cleaning/rotation every 100 hours is recommended. A ground run at 800 to 1000 RPM of 60 to 90 seconds duration just prior to shutdown will allow temperature stabilization and burnoff of deposits accumulated during idletown and taxiing. Mixture cutoff should be accomplished at this RPM without returning to idle.

**EXHAUST VALVE STICKING**

Exhaust valve sticking can result from lead salt (sulfated ash) accumulation in the lubricating oil. It is recommended that regular 50 hour oil changes be implemented to reduce such accumulation. A few stuck exhaust valves have been reported where examination of the cylinder assembly revealed an exhaust leak between the exhaust elbow flange and the exhaust port face. This condition created localized cylinder head overheating and subsequent exhaust valve and guide distress.

The exhaust system should be inspected every 100 hours and leaks corrected prior to continued engine operational service.
RECOMMENDED MIXTURELEANING PROCEDURES

The TCM Engine Operator's Manual or the Aircraft Manufacturer's Owners Manual should be Consulted for the proper leaning procedures applicable to each model engine. Leaning as specified Will reduce spark plug fouling.

The following chart identifies the fuels consired acceptable for use in TCM engines provid the Foregoing recommendations are implemented:

<table>
<thead>
<tr>
<th>SERIES</th>
<th>SPECIFIED FUEL</th>
<th>ALTERNATE FUELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A65, A75, C75</td>
<td>80/87</td>
<td>+100LL</td>
</tr>
<tr>
<td>C85, C90, C125, C145</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E165, E185, E225</td>
<td>80/87</td>
<td>+100LL</td>
</tr>
<tr>
<td>O-200, O-300, GO-300</td>
<td>80/87</td>
<td>+100LL</td>
</tr>
<tr>
<td>IO-360, TSIO-360</td>
<td>100/130</td>
<td>100, 100LL, 115/145</td>
</tr>
<tr>
<td>LTSIO-360</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-346</td>
<td>91/96</td>
<td>100, 100LL, 115/145</td>
</tr>
<tr>
<td>O-470-4,-11,-13,-15</td>
<td>80/87</td>
<td>+100LL</td>
</tr>
<tr>
<td>0-470-A,-F,-J,-K,-L,-R,-S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O470-B,-G,-H,-M,-N,-P</td>
<td>91/96</td>
<td>100,100LL, 115/145</td>
</tr>
<tr>
<td>O470-I,-U</td>
<td>100LL</td>
<td>100, 115/145</td>
</tr>
<tr>
<td>LIO-470,IO-470-A,-C,-G,-P,-T</td>
<td>91/96</td>
<td>100,100LL, 115/145</td>
</tr>
<tr>
<td>IO-470-D,-E,-F,-H,-I,-M,-N,-S,-U,-V,-VO</td>
<td>100/130</td>
<td>100, 100LL, 115/145</td>
</tr>
</tbody>
</table>

Note: +the use of Grade 100LL is highly recommended when the specified fuel is not available, however. Grade 100 may be used for limited operation when Grade 80 or 100LL is not available.

All TCM engines which were certificated on 91/96 octane or grade 100/130 aviation gasoline will Operate satisfactorily on Grade 100 LL or military Grade 115/145. It is recommended that Grade 100LL Be used in these engines because of the reduction in combustion chamber deposits realized with the lower TEL content.
USE OF AUTOMOTIVE FUEL IN TCM AIRCRAFT ENGINES

TCM does not recommend or authorize the use of automotive fuels in any of their aircraft engines. The engine warranty and pro rata policy will be voided if such fuels are utilized. Fuels must conform to ASTM-D910 or MIL-G-5572E, if satisfactory engine service life is anticipated.

Automotive fuels can contain additives that act as corrosive agents, formulate gum deposits and therefore, increases combustion chamber deposits. Continued operation on automotive fuel can lead to detonation, pre-ignition and sticking or eroded valves.

The vapor pressure of automotive fuels exceeds that allowable for aviation fuels. This increased vapor pressure increases the tendency to vapor lock at higher altitudes. A vapor lock condition can cause complete power loss.

The use of any fuel that does not conform to the above specifications may cause cylinder assembly, valve, piston and/or piston ring damage/failure.
DATE: July 16, 2010
Service Instruction No. 1070Q
(Supersedes Service Instruction No. 1070P)
Engineering Aspects are
FAA (DER) Approved

SUBJECT: Specified Fuels

MODELS AFFECTED: All Lycoming aircraft engine models

TIME OF COMPLIANCE: When refueling aircraft

This service instruction specifies the fuels that are to be used when refueling Lycoming aircraft engines. Acceptable fuels for Lycoming Engines are listed in the following sections in this Service Instruction:

- Section A - Aviation fuels
- Section B - Unleaded automotive fuels

⚠️ CAUTION

Any mixture of unapproved fuels and additive materials that results in a lower than specified octane rating can cause engine damage. Use of lower-than-required octane may cause detonation and mechanical damage to the engine.

⚠️ CAUTION

If the incorrect fuel or additives are used, refer to the latest revision of Service Bulletin No. 398 for instructions to correct the fuel contamination.
Section A - Aviation Fuels

Domestic and foreign leaded aviation fuel grades listed in Table A-1 are still applicable for use in all Lycoming engines. Leaded aviation fuel grades 91/96 and 115/145 have been discontinued and have been replaced by the low lead grade fuel: 100LL. Leaded aviation fuel grade 80/87 has limited availability in the U.S. as well as overseas. Commercial fuel grades 100 and 100/130 having Tetraethyl Lead (TEL) content of up to 4ml/U.S. gallons are approved for use in all engines certified for use with grade 100/130 fuel.

TABLE A-1
AVIATION GASOLINE FUELS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>80/87</td>
<td>Red</td>
<td>0.5</td>
<td>80</td>
<td>Red</td>
<td>0.5</td>
<td>AVGAS 91/96UL*</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>91/96</td>
<td>Blue</td>
<td>2.0</td>
<td>100LL</td>
<td>Blue</td>
<td>2.0</td>
<td>B91/115**</td>
<td>Green</td>
<td>•</td>
</tr>
<tr>
<td>100/130</td>
<td>Green</td>
<td>3.0</td>
<td>100</td>
<td>Green</td>
<td>3.0</td>
<td>B95/130**</td>
<td>Amber</td>
<td>•</td>
</tr>
</tbody>
</table>

* Trade name for colorless unleaded fuel produced by Hjelmco Oil, Inc. of Sollentuna, Sweden and stated by the company to conform to ASTM D910 specifications except for the lead content and colorant. Specification of Hjelmco AVGAS 91/96UL (or any other brand/trade name) does not constitute a commercial endorsement by Lycoming.

** B91/115 and B95/130 are available for use in the Commonwealth of Independent States (CIS). Fuel currently designated 91 is available for use in Ukraine. These fuels are specified by GOST1012-72. Max. TEL content is 2.5g/kg (B91/115) and 3.1g/kg (B95/130). Ukrainian 91 is specified by TU38.5901481-96. Max. TEL content is 2.5g/kg.

In some overseas countries, grade 100LL fuel is colored green and designated as “100L”.

If fuels specified in Table A-1 are not available, a higher grade leaded aviation fuel listed in Table A-2, as an alternative, may be used and are subject to the restrictions described in the footnotes. Although Table A-1 lists specified and alternate fuels that can be used safely, this list in no instance permits use of fuels of a lower grade. Any fuel used in Lycoming engines must conform to Specifications ASTM-D910 and MIL-G-5571F.

NOTE
Isopropyl alcohol in amounts not to exceed 1% by volume may be added to the aviation fuel (not automotive fuel) to prevent ice formation in fuel lines and tanks. Although approved for use in Lycoming engines, do not use isopropyl alcohol in the aircraft fuel systems unless recommended by the aircraft manufacturer.
<table>
<thead>
<tr>
<th>Engine Models</th>
<th>SPECIFIED FUELS</th>
<th>Alternate Military and Commercial Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASTM D910</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Certified For Use With Grade</td>
<td>Commercial Grade Designation</td>
</tr>
<tr>
<td>O-215-B,-E,-H; O-200-D; O-435-A,-C</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>O-290-D2; O-320-A,-C,-E; IO-320-A,-E; AEIO-520-E; O-340-E; O-360-B,-D; GO-435-C2; VO-435-A; GO-480-B,-D,-F; O-540-B; VO-540-A,-B</td>
<td>80/87</td>
<td>80</td>
</tr>
<tr>
<td>O-330-B,-D; IO-330-B,-D; LIO-330-B1A; AEIO-330-D; AIO-320-A,-B,-C; O-360-A,-C,-F,-G,-I; IO-360-B,-E,-L,-M; LO-360-A; AEIO-360-B,-H; VO-360-A,-B; TVO-360-A; HIO-360-A,-B,-C; HIO-360-B; O-435-A; GO-435-C2; O-480-A; O-540-A,-D,-E,-F,-G,-H; IO-540-C,-D,-E,-N,-T; AEIO-540-D;</td>
<td>91/96</td>
<td>100LL</td>
</tr>
<tr>
<td>TO-360-A,-C; TIO-360-A; TVO-435-A,-B,-C,-D,-E,-F,-G; GSIO-480-A,-B; IGSIO-480-A,-B; TIO-540-A,-C,-D,-E,-F,-G,-H; JN-300,-R; S,-U,-V,-W,-AA,-AB,-AE,-AF,-AG,-AH,-AJ,-AK; LTI0-540-F,-J,N,-R,-U,-V; TVIO-540-A; IOSIO-540-A,-B; TIO-541-A,-E; TIOG-541-B,-C,-D,-E,-G;</td>
<td>100/130</td>
<td>100LL</td>
</tr>
<tr>
<td>O-330-B; G-360-E; LO-360-E; O-540-J,-L; HIO-360-FLAD</td>
<td>100LL or 100</td>
<td>100LL or 100</td>
</tr>
</tbody>
</table>

* - GO-435-C2 engines with Marvel Schebler carburetor No. 10-3991 are certified to use 91/96 fuel.
Grade 100LL or 100L in which the lead content is limited to 2 ml. of TEL per gallon are approved for continuous use in all Lycoming engines listed herein. Inspection procedures described in the following footnotes are not required for engines using this fuel.

O-235-C, O-290-D, -D2 and O-435-A2, -K1 (O-435-4) engines were built with solid stem exhaust valves. The use of fuels with higher lead content of more than 2 ml. of TEL per U.S. gallon must be limited to 25% of the operating time. If specified fuel is not available and usage with high leaded fuel exceeds 25% of the operating time, inspect the valve stems at every 150 hours of engine operation for erosion or “necking”. This inspection is accomplished by removing the exhaust manifold and visually inspecting the valves through exhaust ports. To determine if an engine has solid stem exhaust valves, remove the rocker cover and look for valve rotor caps which are used with sodium cooled valves but not with solid stem valves in these particular engines. O-235-C and O-290-D models can be converted to use sodium cooled exhaust valves. See latest revision of Service Instruction No. 1246 for procedure.

Early production O-320-A, -C, -D, GO-435, VO-435-A and GO-480-B, -D, -F were built with solid stem exhaust valves and their use with fuels having lead content of more than 2 ml. of TEL per U.S. gallon is limited to 25% of the operating time. If specified fuel is not available and usage with high leaded fuel exceeds 25% of the operating time, inspect the valve stems at 150 hours of engine operation for erosion or “necking”. This inspection is accomplished by removing the exhaust manifold and visually inspecting the valves through exhaust ports. To determine if an engine has solid stem exhaust valves, remove the rocker cover and look for valve rotor caps which are used with sodium cooled valves but not with solid stem valves in these particular engines.

Continuous use of high lead fuels can result in increased lead deposits both in combustion chambers and spark plugs causing engine roughness and scored cylinder walls. It is recommended that the use of this fuel be limited wherever possible; however, when high lead fuel is used, conduct periodic inspections of combustion chambers, valves and valve ports more frequently and rotate or clean spark plugs whenever lead fouling is experienced. See latest revision of Service Letter No. L192.

See latest revision of Service Letter No. L183 for operating recommendations.
Section B - Unleaded Automotive Fuels

This Section B supplies critical details on the use of automotive fuel in aircraft engines.

Premium or Super Premium grade unleaded automotive gasoline fuels meeting the requirements identified in Table B-1 of this Service Instruction are approved for use only on the engine models listed in Table B-2. Usage of automotive gasoline that does not conform to the parameters described in Tables B-1 and B-2 is not permitted.

⚠️ CAUTION

Automotive ground transportation fuels available direct to consumers (e.g., "pump gas") are typically not labeled sufficiently to determine compliance with the requirements stipulated in Table B-1. While indicated octane is generally required for display at retail points of sale, octane rating methods, fuel vapor pressure, oxygenate content and ethanol content can vary widely and are generally known only at the wholesale terminal. To ensure compliance with Service Instruction No. 1070Q, all parameters listed in Table B-1 must be satisfied.

Background

Automotive ground transportation fuels have previously been prohibited for use in all Lycoming engines. The primary reason for this prohibition is the fact that ground transportation fuels (gasoline and diesel) are generally formulated to optimize engine emissions and ease-of-starting. These formulations are heavily influenced by environmental regulations and vary by geographic region and season.

Automotive fuel specifications have evolved in recent years such that ASTM/EN standard fuel ordering parameters may be utilized to stipulate the necessary properties to enable usage as an aviation fuel for aircraft engines with low octane requirements. The control parameters that must be specified and examined for compliance in aviation use are the same as the parameters that must be specified in automotive ground transport use.

NOTE

Although the automotive fuel listed in Table B-1 is approved for use in the Lycoming engine models listed in Table B-2, further approval is required via a Supplemental Type Certificate (STC) or Type Certificate (TC) to permit the use of this fuel in the airframe.

Description

The clear, colorless unleaded automotive fuels listed in Table B-1 must conform to ASTM D4814-09b or EN 228:2008-E. In these specifications, the automotive fuel is classified by an Anti-Knock Index (AKI) or in the case of EN228 Super Premium, a grade designation. The AKI is an octane rating and is the arithmetic average of the Research Octane Number (RON) and Motor Octane Number (MON).

\[(\text{RON} + \text{MON})/2 = \text{AKI}\]

The AKI or EN228 grade value must be as specified in Table B-2 or higher. The AKI or grade value is critical to engine performance. Table B-2 lists the selected Lycoming engine models and the minimum AKI or grade requirement.

As per ASTM D4814-09b, the vapor pressure of the fuel must be rated as Class A-4 for vapor lock protection. The letter “A” in this rating refers to the volatility of the fuel and the number specifies the vapor lock protection class. The ASTM D4814-09b maximum vapor pressure limit is 9.0 psi (0.62 kPa) maximum for a Class A rating. Vapor lock can occur at high operating temperatures resulting in diminished fuel flow to the engine causing loss of engine power, rough engine operation, or engine stoppage.
CAUTION

Automotive fuels typically have Reid Vapor Pressure (RVP) values between 7 and 9.3 psi (0.48 and 0.64 kPa) in summer seasons. Automotive fuel specifications allow as high as 15 psi (1.03 kPa) in the winter. In some geographic regions, there is no upper limit to RVP in the winter season. As vapor pressure increases, the tendency for vapor lock will increase as well as fuel "boil off" at altitude.

CAUTION

Ethanol is not allowed. Ethanol-based fuels may not be compatible with some fuel system components. In cases of materials incompatibility, deterioration of metallic and non-metallic components can occur.

Another key aspect of using automotive fuel as aviation fuel is that the fuel must be free of undissolved water, sediment, and suspended matter.

### TABLE B-1

**UNLEADED AUTOMOTIVE FUEL SPECIFICATION REQUIREMENTS**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Color</th>
<th>Grade</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>See Table B-2</td>
<td>Clear</td>
<td>See Table B-2</td>
<td>Clear</td>
</tr>
</tbody>
</table>

*ASTM D4814-09b, Approved September 2009, must conform to the following requirements:
- Octane: See Table B-2
- Vapor Pressure: Class A-4
- Oxygenates: Less than 1% (NO ETHANOL)

**EN 228:2008:E, Approved July 2008, must conform to the following requirements:
- Octane: See Table B-2
- Vapor Pressure: Class A
- Oxygenates: Less than 1% (NO ETHANOL)

### TABLE B-2

**ENGINE MODELS APPROVED FOR UNLEADED (TABLE 1) AUTOMOTIVE FUEL**

<table>
<thead>
<tr>
<th>Lycoming Engine Models</th>
<th>ASTM D4814 Minimum AKI Required (RON+MON)/2</th>
<th>EN228 Minimum Grade Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-360 series A, C, F, G &amp; J engines</td>
<td>93</td>
<td>NB.3</td>
</tr>
<tr>
<td>HO-360-C1A</td>
<td>93</td>
<td>NB.3</td>
</tr>
<tr>
<td>LIO-360-M1A</td>
<td>93</td>
<td>NB.3</td>
</tr>
<tr>
<td>LO-360-A1H6</td>
<td>93</td>
<td>NB.3</td>
</tr>
</tbody>
</table>

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**ISSUED**


**REVISED**


**PAGE NO.**


**REVISION**


0.1 1070
Standard Specification for High Octane Unleaded Test Fuel

This standard is issued under the fixed designation D7719; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reaffirmation. A superscript epsilon (e) indicates an editorial change since the last revision or reaffirmation.

INTRODUCTION

This new test fuel specification is for a high-octane unleaded fuel to be used for gathering data toward a commercial research report and specification on an unleaded high-octane aviation gasoline.

A new high-octane unleaded test fuel has been developed which maintains the key performance parameters of existing reciprocating aircraft engines. The two essential performance parameters of MON and VP are inversely related with respect to composition and thus can uniquely define a composition range of the two components. The values for VP and MON in Table 1 reflect the limiting values of the two components. The binary fuel exhibits a higher volumetric energy density (net heat of combustion times density) which is of great performance interest, although not explicitly stated in Table 1. The distillation parameters reflect the binary compositional effects. This is an unleaded fuel, so the limit of TEL in Table 1 is the same as is used in Specification D4814 for mogas and is meant to mitigate unintentional contamination by TEL. Lastly, references to dyes remain in the specification so that test groups may use them as necessary.

1. Scope

1.1 This specification covers formulating specifications for purchases of a high octane unleaded test fuel under contract and is intended solely for use by purchasing agencies for testing purposes.

1.2 This specification defines a specific type of high octane unleaded test fuel for use as an aviation spark-ignition fuel.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

2. Referenced Documents

2.1 ASTM Standards:

D85 Test Method for Distillation of Petroleum Products at Atmospheric Pressure

D130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test

D323 Test Method for Vapor Pressure of Petroleum Products (Reid Method)

D873 Test Method for Oxidation Stability of Aviation Fuels (Potential Residue Method)

D1094 Test Method for Water Reaction of Aviation Fuels

D1266 Test Method for Sulfur in Petroleum Products (Lamp Method)

D1298 Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method

D2385 Test Method for Freezing Point of Aviation Fuels

D2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry

D2624 Test Methods for Electrical Conductivity of Aviation and Distillate Fuels

D2700 Test Method for Motor Octane Number of Spark-Ignition Engine Fuel

D3237 Test Method for Lead in Gasoline by Atomic Absorption Spectroscopy

D4052 Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter

D4057 Practice for Manual Sampling of Petroleum and Petroleum Products

D4171 Specification for Fuel System Icing Inhibitors

D4177 Practice for Automatic Sampling of Petroleum and Petroleum Products

D4306 Practice for Aviation Fuel Sample Containers for Tests Affected by Trace Contamination

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Copyright © ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.
D4809 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)
D4814 Specification for Automotive Spark-Ignition Engine Fuel
D5006 Test Method for Measurement of Fuel System Icing Inhibitors (Ethereal Type) in Aviation Fuels
D5059 Test Methods for Lead in Gasoline by X-Ray Spectroscopy
D5190 Test Method for Vapor Pressure of Petroleum Products (Automatic Method)
D5191 Test Method for Vapor Pressure of Petroleum Products (Manual Method)
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

3. Terminology

3.1 Definitions:
3.1.1 aviation gasoline fuel, n—fuel possessing specific properties suitable for operating aircraft powered by reciprocating spark-ignition engines.
3.1.2 binary, adj—characterized by, or consisting of, two components.
3.1.3 biomass, n—plant material, vegetation, or agricultural waste used as a fuel or energy source.
3.1.4 high-octane, adj—possessing a motor octane number (MON) greater than 100.

4. General

4.1 This specification, unless otherwise provided, prescribes the required properties of a binary aviation fuel at the time and place of delivery.

5. Classification

5.1 One grade of high octane unleaded test fuel is provided, known as UL102.

6. Materials and Manufacture

6.1 High octane unleaded test fuel, except as otherwise specified in this specification, shall consist of blends of refined reformate hydrocarbons. The sources for these hydrocarbons include biomass, natural gas, or crude petroleum.
6.1.1 See Appendix X1 for one particular composition being test that meets the parameters of Table 1

6.2 Additives—These can be added to each grade of high-octane unleaded aviation fuel in the amount, and of the composition, specified in the following list of approved materials:
6.2.1 Dyes—The total maximum concentration of dye in the fuel is 6.0 mg/L.
6.2.1.1 The only blue dye present in the finished fuel shall be essentially 1,4-diakylaminonaphthaquinone.
6.2.1.2 The only yellow dyes in the finished fuel shall be essentially p-diethylaminobenzidine (Color Index No. 11021) or 1,3-benzendiol 2.4-bis [(alkylphenyl)azo-].
6.2.1.3 The only red dye present in the finished fuel shall be essentially alkyl derivatives of azobenzene-4-azo-2-naphthol.
6.2.1.4 The only orange dye present in the finished fuel shall be essentially benzene-azo-2-naphthol (Color Index No. 12055).
6.2.2 Other Additives—These may be added in the amount and of the composition specified in the following list of approved materials. The quantities and types shall be declared by the manufacturer. Additives added after the point of manufacture shall also be declared.
6.2.2.1 Antioxidants—The following oxidation inhibitors may be added to the fuel separately, or in combination, in total

<table>
<thead>
<tr>
<th>Table 1 Detailed Requirements for High Octane Unleaded Test Fuel</th>
<th>Grade UL102</th>
<th>ASTM Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knockdown, Motor Octane Number</td>
<td>min</td>
<td>102.2</td>
</tr>
<tr>
<td>Density at 15°C, kg/m³</td>
<td>min</td>
<td>790</td>
</tr>
<tr>
<td>max</td>
<td>825</td>
<td></td>
</tr>
<tr>
<td>Distillation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial boiling point, °C</td>
<td>Report</td>
<td></td>
</tr>
<tr>
<td>Fuel (evaporated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 volume % at °C</td>
<td>min</td>
<td>75</td>
</tr>
<tr>
<td>max</td>
<td>100</td>
<td>D86</td>
</tr>
<tr>
<td>60 volume % at °C</td>
<td>min</td>
<td>135</td>
</tr>
<tr>
<td>max</td>
<td>165</td>
<td>D86</td>
</tr>
<tr>
<td>80 volume % at °C</td>
<td>min</td>
<td>180</td>
</tr>
<tr>
<td>max</td>
<td>230</td>
<td>D86</td>
</tr>
<tr>
<td>Final boiling point, °C</td>
<td>max</td>
<td>180</td>
</tr>
<tr>
<td>Sum of 10% + 10% evaporated temperatures, °C</td>
<td>min</td>
<td>135</td>
</tr>
<tr>
<td>max</td>
<td>165</td>
<td>D86</td>
</tr>
<tr>
<td>Racerosity, volume %</td>
<td>min</td>
<td>97</td>
</tr>
<tr>
<td>max</td>
<td>1.5</td>
<td>D86</td>
</tr>
<tr>
<td>Loss, volume %</td>
<td>max</td>
<td>1.5</td>
</tr>
<tr>
<td>Vapor pressure, 37.8°C, kPa</td>
<td>min</td>
<td>38.0</td>
</tr>
<tr>
<td>max</td>
<td>49.0</td>
<td></td>
</tr>
<tr>
<td>Freezing point, °C</td>
<td>max</td>
<td>-58</td>
</tr>
<tr>
<td>Sulfur, mass %</td>
<td>max</td>
<td>0.05</td>
</tr>
<tr>
<td>Not heat of combustion, MJ/kg</td>
<td>min</td>
<td>41.5</td>
</tr>
<tr>
<td>Corrosion, copper strip, 2 h at 100°C</td>
<td>max</td>
<td>No. 1</td>
</tr>
<tr>
<td>Oxidation stability (6 h aging)</td>
<td>max</td>
<td>6</td>
</tr>
<tr>
<td>Potential gum, mg/100 mL</td>
<td>max</td>
<td>0.1</td>
</tr>
<tr>
<td>Water reaction</td>
<td>max</td>
<td>1.2</td>
</tr>
<tr>
<td>Electrical conductivity, pSm</td>
<td>max</td>
<td>450</td>
</tr>
<tr>
<td>Tetrasulfated Lead, g Pb/L</td>
<td>max</td>
<td>0.013</td>
</tr>
</tbody>
</table>
concentration not to exceed 12 mg of inhibitor (not including weight of solvent) per litre of fuel.

(1) 2,6-ditertiary butyl-4-methylphenol.
(2) 2,4-dimethyl-6-tertiary butylphenol.
(3) 3,6-ditertiary butylphenol.
(4) 75 % minimum 2,6-ditertiary butylphenol plus 25 % maximum mixed tertiary and tritertiary butylphenols.
(5) 75 % minimum di- and tri-isopropyl phenols plus 25 % maximum di- and tritertiary butylphenols.
(6) 72 % minimum 2,4-dimethyl-6-tertiary butylphenol plus 28 % maximum monomethyl and dimethyl tertiary butylphenols.
(7) N,N'-di-isopropyl-para-phenylenediamine.

6.2.2.2 Fuel System Inhibiting Additive (FSI)—One of the following materials may be used:

(1) Isopropyl Alcohol (IPA, prop-2-ol), in accordance with the requirements of Specification D4171 (Type II). May be used in concentrations recommended by the aircraft manufacturer when required by the aircraft owner/operator.

(2) Di-Ethylene Glycol Monomethyl Ether (Di-EGME), conforming to the requirements of Specification D4171 (Type III). May be used in concentrations of 0.10 to 0.15 volume % when required by the aircraft owner/operator.

(3) Test Method D506 can be used to determine the concentration of Di-EGME in aviation fuels.

Note 1—Addition of isopropyl alcohol (IPA) may reduce knock ratings below minimum specification values.

6.2.2.3 Electrical Conductivity Additive—Stadis 450 in concentrations up to 3 mg/L is permitted. When loss of fuel conductivity necessitates retreatment with electrical conductivity additive, further addition is permissible.

6.2.2.4 Corrosion Inhibitor Additive—The following corrosion inhibitors may be added to the fuel in concentrations not to exceed the maximum allowable concentration (MAC) listed for each additive.

- DCH-4A MAC = 24.0 g/m³
- DCH-6A MAC = 15.0 g/m³
- HITEC 580 MAC = 22.5 g/m³
- NALCO 5402 MAC = 29.5 g/m³
- NALCO 5406 MAC = 11.0 g/m³
- UNICOR J MAC = 22.5 g/m³
- SPEC-AD 5020 MAC = 24.0 g/m³
- TOLAD 30 MAC = 24.0 g/m³
- TOLAD 440 MAC = 22.5 g/m³

7. Detailed Requirements

7.1 The high octane unleaded test fuel shall conform to the requirements prescribed in Table 1.

7.2 Test results shall not exceed the maximum or be less than the minimum values specified in Table 1. No allowance shall be made for the precision of the test methods. To determine the conformance to the specification requirement, a test result may be rounded to the same number of significant figures as in Table 1 using Practice E29. Where multiple determinations are made, the average result, rounded according to Practice E29, shall be used.

8. Workmanship, Finish and Appearance

8.1 The high octane unleaded test fuel specified in this specification shall be free from undissolved water, sediment, and suspended matter. No substances of known dangerous toxicity, under usual conditions of handling and use, shall be present except as permitted in this specification.

9. Sampling

9.1 Because of the importance of proper sampling procedures in establishing fuel quality, use the appropriate procedures in Practice D4057 or Practice D4177.

9.1.1 Although automatic sampling following Practice D4177 may be useful in certain situations, initial manufacturer/ supplier specification compliance testing shall be performed on a sample taken following procedures in Practice D4057.

9.2 A number of high octane unleaded test fuel properties, including copper corrosion, electrical conductivity, and others are very sensitive to trace contamination which can originate from sample containers. For recommended sample containers, refer to Practice D4306.

10. Reports

10.1 The type and number of reports to ensure conformance with the requirements of this specification shall be mutually agreed to by the purchaser and the supplier of the high octane unleaded test fuel.

11. Test Methods

11.1 The requirements enumerated in this specification shall be determined in accordance with the following ASTM test methods:

11.1.1 Knock Value (Lean Rating)—Test Method D2700.
11.1.2 Tetracetyl Lead—Test Methods D3237 or D5659.
11.1.3 Density—Test Methods D1298 or D4052.
11.1.4 Distillation—Test Method D86.
11.1.5 Freezing Point—Test Method D2836.
11.1.6 Vapor Pressure—Test Methods D232, D5190, or D5191.
11.1.7 Net Heat of Combustion—Test Method D4809.
11.1.8 Sulfur—Test Methods D1266 or D2622.
11.1.9 Corrosion (Copper Strip)—Test Method D130, 2 h test at 100°C in bomb.
11.1.10 Potential Gum and Visible Lead Precipitate—Test Method D873 except that wherever the letter X occurs (referring to oxidation time) insert the number 5, designating the number of hours prescribed in this specification.
11.1.12 Electrical Conductivity—Test Method D2624.

12. Keywords

12.1 aviation fuel; binary; high-octane; unleaded
APPENDIX

(X1. NONMANDATORY INFORMATION)

X1. BINARY FUEL COMPOSITION

X1.1 Introduction

X1.1.1 This specification covers a high octane unleaded test fuel developed for existing spark-ignition aircraft engines. The specification is being proposed for testing purposes only.

X1.2 Composition

X1.2.1 The origin of the fuel lies in two essential engine performance parameters: Motor Octane Number, and Vapor Pressure. Fig. X1.1 shows the inverse relationship of these two parameters as a function of mesitylene composition.

X1.2.2 These two parameters coupled with the fact that the fuel is a binary composition, fix the effective composition range as follows:

1. High Octane Composition: 84% mesitylene 16% isopentane
2. High Limit Reid Composition 79% mesitylene 21% isopentane

X1.2.3 These limits are proposed to define the binary fuel’s test fuel specification composition.

![Graph showing Motor Octane Number and Vapor Pressure vs. wt% Mesitylene](image_url)
Designation: D910 – 11

Standard Specification for Aviation Gasolines

This standard is issued under the fixed designation D910; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reaffirmation. A superscript epsilon (ε) indicates at editorial change since the last revision or reaffirmation.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This specification covers formulating specifications for purchases of aviation gasoline under contract and is intended primarily for use by purchasing agencies.

1.2 This specification defines specific types of aviation gasolines for civil use. It does not include all gasolines satisfactory for reciprocating aviation engines. Certain equipment or conditions of use may permit a wider, or require a narrower, range of characteristics than is shown by this specification.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

2. Referenced Documents

2.1 ASTM Standards:

D85 Test Method for Distillation of Petroleum Products at Atmospheric Pressure
D93 Test Method for Flash Point by Pensky-Martens Closed Cup Tester
D130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test
D325 Test Method for Vapor Pressure of Petroleum Products (Reid Method)
D357 Method of Test for Knock Characteristics of Motor Fuels Below 100 Octane Number by the Motor Method
D381 Test Method for Gum Content in Fuels by Jet Evaporation
D614 Method of Test for Knock Characteristics of Aviation Fuels by the Aviation Method

D873 Test Method for Oxidation Stability of Aviation Fuels (Potential Residue Method)
D909 Test Method for Supercharge Rating of Spark-Ignition Aviation Gasoline
D1094 Test Method for Water Reaction of Aviation Fuels
D1266 Test Method for Sulfur in Petroleum Products (Lamp Method)
D1298 Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
D1948 Method of Test for Knock Characteristics of Motor Fuels Above 100 Octane Number by the Motor Method
D2386 Test Method for Freezing Point of Aviation Fuels
D2392 Test Method for Color of Dyed Aviation Gasolines
D2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry
D2624 Test Method for Electrical Conductivity of Aviation and Distillate Fuels
D2703 Test Method for Motor Octane Number of Spark-Ignition Engine Fuel
D3338 Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
D3341 Test Method for Lead in Gasoline—Iodine Monochloride Method
D4052 Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter
D4057 Practice for Manual Sampling of Petroleum and Petroleum Products
D4171 Specification for Fuel System Icing Inhibitors
D4177 Practice for Automatic Sampling of Petroleum and Petroleum Products
D4325 Practice for Aviation Fuel Sample Containers for Tests Affected by Trace Contamination
D4529 Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
D4809 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)
D4865 Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems
D5006 Test Method for Measurement of Fuel System Icing Inhibitors (Ether Type) in Aviation Fuels


2 For referenced ASTM standards, visit www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard’s Document Summary page on the ASTM website.

3 Withdrawn. The last approved version of this historical standard is referenced on www.astm.org.

A Summary of Changes section appears at the end of this standard.
6. Materials and Manufacture

6.1 Aviation gasoline, except as otherwise specified in this specification, shall consist of blends of refined hydrocarbons derived from crude petroleum, natural gasoline, or blends, thereof, with synthetic hydrocarbons or aromatic hydrocarbons, or both.

6.2 Additives—Mandatory, shall be added to each grade of aviation gasoline in the amount and of the composition specified in the following list of approved materials.

6.2.1 Tetraethyl Lead, shall be added in the form of an antiknock mixture containing not less than 61 mass % of tetraethyl lead and sufficient ethylene dibromide to provide two bromine atoms per atom of lead. The balance shall contain no added ingredients other than kerosine, an approved oxidation inhibitor, and blue dye, as specified herein. The maximum concentration limit for each grade of gasoline is specified in Table 1.

6.2.1.1 If mutually agreed upon by the fuel producer and additive vendor, tetraethyl lead antiknock mixture may be diluted with 20 mass % of a mixed aromatic solvent having a minimum flash point of 60°C according to Test Methods D93 when the product is to be handled in cold climates. The TEL content of the dilute product is reduced to 49 mass %, so that the amount of antiknock additive must be adjusted to achieve the necessary lead level. The dilute product still delivers two bromine atoms per atom of lead.

6.2.2 Dyes—The maximum concentration limits in each grade of gasoline are specified in Table 1.

6.2.2.1 The only blue dye that shall be present in the finished gasoline shall be essentially 1,4-dialkyldiaminotetraazaine.

6.2.2.2 The only yellow dyes that shall be present in the finished gasoline shall be essentially p-diethylaminobenzene (Color Index No. 11021) or 1,3-benzenediol 2,4-bis (alkylphenylazo)-.

6.2.2.3 The only red dye that shall be present in the finished gasoline shall be essentially alkyl derivatives of azobenzene-4-azo-2-naphthol.

6.2.2.4 The only orange dye that shall be present in the finished gasoline shall be essentially benzene-azo-2-naphthol (Color Index No. 12055).

6.3 Additives—These may be added to each grade of aviation gasoline in the amount and of the composition specified in the following list of approved materials.3 The quantities and types shall be declared by the manufacturer. Additives added after the point of manufacture shall also be declared.

6.3.1 Antioxidants—The following oxidation inhibitors may be added to the gasoline separately, or in combination, in total concentration not to exceed 12 mg of inhibitor (not including weights of solvent) per litre of fuel.

6.3.1.1 2,6-ditertiary butyl-4-methylphenol.

6.3.1.2 2,4-dimethyl-6-tertiary butylphenol.

6.3.1.3 2,6-ditertiary butylphenol.

3 Supporting data (guidelines for the approval or disapproval of additives) have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:002-125.
### TABLE 1  Detailed Requirements for Aviation Gasolines

<table>
<thead>
<tr>
<th>Octane Ratings</th>
<th>Grade</th>
<th>80</th>
<th>91</th>
<th>100/VEL</th>
<th>100LL</th>
<th>100</th>
<th>ASTM Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knock Value, Lean Mixture</td>
<td>min</td>
<td>85.7</td>
<td>90.0</td>
<td>99.6</td>
<td>99.0</td>
<td>99.6</td>
<td>D2700</td>
</tr>
<tr>
<td>Motor Octane Number</td>
<td>min</td>
<td>85.0</td>
<td>90.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>D2700</td>
</tr>
<tr>
<td>Knock Value, Rich Mixture</td>
<td>min</td>
<td>97.0</td>
<td>98.0</td>
<td>130.0</td>
<td>130.0</td>
<td>130.0</td>
<td>D806</td>
</tr>
<tr>
<td>Octane Number</td>
<td>min</td>
<td>97.0</td>
<td>98.0</td>
<td>130.0</td>
<td>130.0</td>
<td>130.0</td>
<td>D806</td>
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<td>Performance Number</td>
<td>min</td>
<td>85.0</td>
<td>90.0</td>
<td>100.0</td>
<td>100.0</td>
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<td>D806</td>
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<td>Tetaethyl lead, mL</td>
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<td>0.33</td>
<td>0.63</td>
<td>0.53</td>
<td>0.53</td>
<td>D3541 or D3559</td>
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<td>TEL</td>
<td>max</td>
<td>0.14</td>
<td>0.46</td>
<td>0.56</td>
<td>0.66</td>
<td>0.66</td>
<td>0.66</td>
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<tr>
<td>gPb</td>
<td>max</td>
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<td>0.3</td>
<td>2.7</td>
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<td>2.7</td>
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<td>Dye content</td>
<td>max</td>
<td>0.2</td>
<td>0.3</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
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<td>Blue dye, mg/L</td>
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<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Yellow dye, mg/L</td>
<td>max</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
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<tr>
<td>Orange dye, mg/L</td>
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<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
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<td>Requirements for All Grades</td>
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</tr>
<tr>
<td>Density at 15°C, kg/m³</td>
<td>Report</td>
<td>D1250 or D4092</td>
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<tr>
<td>Distillation</td>
<td>Report</td>
<td>D86</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Initial boiling point, °C</td>
<td>max</td>
<td>75</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>Final boiling point, °C</td>
<td>max</td>
<td>170</td>
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<td></td>
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<tr>
<td>Sum of 10% 50% Evaporated</td>
<td>min</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovery volume %</td>
<td>max</td>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual volume %</td>
<td>max</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss volume %</td>
<td>max</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor pressure, 38°C, kPa</td>
<td>max</td>
<td>38.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freezing point, °C</td>
<td>max</td>
<td>-30°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur mass %</td>
<td>max</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen content, %</td>
<td>max</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper strip, 2 h at 100°C</td>
<td>max</td>
<td>No. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxidation stability, 5 h aging</td>
<td>min</td>
<td>10 hh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorus, mg/100 mL</td>
<td>max</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead, mg/100 mL</td>
<td>max</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water reaction</td>
<td>max</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge</td>
<td>max</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical conductivity, pS/m</td>
<td>max</td>
<td>450 pS/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. For compliance with the requirements of Table 1, see 7.2.
2. The test methods indicated in this table shall be referred to in Section 11.
3. Both Motor Octane Number (MON) and Aviator Lean Mixture number shall be reported.
4. A performance number of 130.0 is equal to a knock value determined using 10 octane plus 0.2 mL TEL.
5. Knock ratings shall be reported to the nearest 0.1 octane/performance number.
6. The maximum dye concentrations shown do not include solvent or dyes supplied in liquid form.
7. Test Method D2919 shall be the reference vacuum pressure method.
8. If no crystals have appeared in cooling to 25°C, the freezing point may be reported as less than 25°C.
9. For all grades using either Test Method D4332 or D4333 in Table 1, in Test Method D4329 or D4330, Test Method D4000 may be used as an alternative. It is a case of dispute, Test Method D4000 shall be used.
10. The maximum dye concentrations shown do not include solvent or dyes supplied in liquid form.
11. The supplier shall report the amount of additive added.
6.3.1.4 75 % minimum 2,6-diteriary butylphenol plus 25 % maximum mixed tertiary and tri-tertiary butylphenols.
6.3.1.5 75 % minimum di- and tri-isopropyl phenols plus 25 % maximum di- and tri-tertiary butylphenols.
6.3.1.6 72 % minimum 2,4-dimethyl-6-tertiary butylphenol plus 28 % maximum monomethyl and dimethyl tertiary butylphenols.
6.3.1.7 N,N' di-isopropyl-para-phenylene diamine.
6.3.1.8 N,N'-di-tertiary-butyl-para-phenylene diamine.
6.3.2 Fuel System Icing Inhibitor (FSI)—One of the following may be used.
6.3.2.1 Isopropyl Alcohol (IPA, propan-2-ol), in accordance with the requirements of Specification D4171 (Type I). May be used in concentrations recommended by the aircraft manufacturer when required by the aircraft owner/operator.

Note 3—Addition of isopropyl alcohol (IPA) may reduce knock ratings below minimum specification values (see X1.2.4).\(^4\)

6.3.2.2 Di Ethylene Glycol Monoethyl Ether (DEGME), conforming to the requirements of Specification D4171 (Type III). May be used in concentrations of 0.10 to 0.15 volume % when required by the aircraft owner/operator.

6.3.2.3 Test Method D5006 can be used to determine the concentration of DEGME in aviation fuels.

6.3.3 Electrical Conductivity Additive—Stadis 450 in concentrations up to 3 mg/L is permitted. When loss of fuel conductivity necessitates retreatment with electrical conductivity additive, further addition is permissible up to a maximum cumulative level of 5 mg/L of Stadis 450.

6.3.4 Corrosion Inhibitor Additive—The following corrosion inhibitors may be added to the gasoline in concentrations not to exceed the maximum allowable concentration (MAC) listed for each additive.

<table>
<thead>
<tr>
<th>Additive</th>
<th>MAC (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCH-4A</td>
<td>22.5</td>
</tr>
<tr>
<td>DCH-4A</td>
<td>22.5</td>
</tr>
<tr>
<td>HITEC 580</td>
<td>22.5</td>
</tr>
<tr>
<td>NALCO 5400</td>
<td>22.5</td>
</tr>
<tr>
<td>NALCO 5405</td>
<td>11.0</td>
</tr>
<tr>
<td>PPR 10</td>
<td>22.5</td>
</tr>
<tr>
<td>UNICOR J</td>
<td>22.5</td>
</tr>
<tr>
<td>SPEC-AID 8252</td>
<td>24.0</td>
</tr>
<tr>
<td>TOLAD 201</td>
<td>24.0</td>
</tr>
<tr>
<td>TOLAD 4410</td>
<td>22.5</td>
</tr>
</tbody>
</table>

7. Detailed Requirements

7.1. The aviation gasoline shall conform to the requirements prescribed in Table 1.

7.2. Test results shall not exceed the maximum or be less than the minimum values specified in Table 1. No allowance shall be made for the precision of the test methods. To determine the conformance to the specification requirement, a test result may be rounded to the same number of significant figures as in Table 1 using Practice E29. Where multiple determinations are made, the average result, rounded according to Practice E29, shall be used.

8. Workmanship, Finish and Appearance

8.1. The aviation gasoline specified in this specification shall be free from undissolved water, sediment, and suspended matter. The odor of the fuel shall not be nauseating or irritating. No substances of known dangerous toxicity under usual conditions of handling and use shall be present except as permitted in this specification.

9. Sampling

9.1. Because of the importance of proper sampling procedures in establishing fuel quality, use the appropriate procedures in Practice D4057 or Practice D4177.

9.1.1. Although automatic sampling following Practice D4177 may be useful in certain situations, initial refinery specification compliance testing shall be performed on a sample taken following procedures in Practice D4057.

9.2. A number of aviation gasoline properties, including copper corrosion, electrical conductivity, and others are very sensitive to trace contamination which can originate from sample containers. For recommended sample containers, refer to Practice D4006.

10. Reports

10.1. The type and number of reports to ensure conformance with the requirements of this specification shall be mutually agreed to by the purchaser and the supplier of the aviation gasoline.

11. Test Methods

11.1. The requirements enumerated in this specification shall be determined in accordance with the following ASTM test methods:

11.1.1 Knock Value (Lean Rating)—Test Method D2700.

11.1.2 Knock Value (Rich Rating)—Test Method D2099.

11.1.3 Tetraethylexide—Test Methods D3341 or D5059.

11.1.4 Color—Test Method D2392.

11.1.5 Density—Test Methods D1298 or D4052.

11.1.6 Distillation—Test Method D86.

11.1.7 Vapor Pressure—Test Methods D233, D5190, or D5191.

11.1.8 Freezing Point—Test Method D2386.

11.1.9 Sulfur—Test Methods D1266 or D2622.

11.1.10 Net Heat of Combustion—Test Methods D4529 or D3338.

11.1.11 Corrosion (Copper Strip)—Test Method D130, 2 h test at 100°C in bomb.

11.1.12 Potential Gum and Visible Lead Precipitate—Test Method D873 except that wherever the letter X occurs (referring to oxidation time) insert the number 5, designating the number of hours prescribed in this specification.


11.1.14 Electrical Conductivity—Test Methods D2624.

12. Keywords

12.1 Avgas; aviation gasoline; gasoline
APPENDIX

(Nonmandatory Information)

XI. PERFORMANCE CHARACTERISTICS OF AVIATION GASOLINES

XI.1 Introduction

XI.1.1 Aviation gasoline is a complex mixture of relatively volatile hydrocarbons that vary widely in their physical and chemical properties. The engines and aircraft impose a variety of mechanical, physical, and chemical environments. The properties of aviation gasoline (Table XI.1) must be properly balanced to give satisfactory engine performance over an extremely wide range of conditions.

XI.1.2 The ASTM requirements summarized in Table 1 are quality limits established on the basis of the broad experience and close cooperation of producers of aviation gasoline, manufacturers of aircraft engines, and users of both commodities. The values given are intended to define aviation gasoline suitable for most types of spark-ignition aviation engines; however, certain equipment or conditions of use may require fuels having other characteristics.

XI.1.3 Specifications covering antiknock quality define the grades of aviation gasoline. The other requirements either prescribe the proper balance of properties to ensure satisfactory engine performance or limit components of undesirable nature to concentrations so low that they will not have an adverse effect on engine performance.

XI.2 Combustion Characteristics (Antiknock Quality and Antiknock Compound Identification)

XI.2.1 The fuel-air mixture in the cylinder of a spark-ignition engine will, under certain conditions, ignite spontaneously in localized areas instead of progressing from the spark. This may cause a detonation or knock, usually inaudible in aircraft engines. This knock, if permitted to continue for more than brief periods, may result in serious loss of power and damage to, or destruction of, the aircraft engine. When aviation gasoline is used in other types of aviation engines, for example, in certain turbine engines where specifically permitted by the engine manufacturer, knock or detonation characteristics may not be critical requirements.

<table>
<thead>
<tr>
<th>TABLE XI.1 Performance Characteristics of Aviation Gasoline</th>
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<tbody>
<tr>
<td><strong>Performance Characteristics</strong></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Combustion characteristics</td>
</tr>
<tr>
<td>Antiknock quality and antiknock compound identification</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Fuel moisture and air ratio</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Carboxy and fuel vaporization</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Corrosion of fuel system and engine parts</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Fluidity at low temperatures</td>
</tr>
<tr>
<td>Fuel cleanliness, handling, and storage stability</td>
</tr>
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</table>

XI.2.2 Aviation gasoline grades are also identified by two numbers separated by a slant line (/). The first number is called the lean mixture rating and the second number is called the rich mixture rating. This specification describes five grades of aviation gasoline as follows: 80/87, 91/98, 100/130, 100/130LL, and 100/130VLL. Numbers below 100 are octave numbers, while numbers above 100 are performance numbers. At 100, octave number and performance number are equal. The suffix LL describes a grade containing lower tetraethyl lead than a second grade of identical lean and rich mixture ratings. The suffix VLL designates a grade containing lower tetraethyl lead than grade 100/130LL of identical lean and rich mixture ratings.

XI.2.3 Both the lean mixture rating and the rich mixture rating are determined in standardized laboratory knock test engines that are operated under prescribed conditions. Results are expressed as octave numbers up to 100 and above this point as quantities of tetraethyl lead added to iso-octane (2,2,4-trimethylpentane). Octane number is defined arbitrarily as the percentage of iso-octane that is that blend of iso-octane and n-heptane that the gasoline matches in knock characteristics when compared by the procedure specified. The quantities of tetraethyl lead added to iso-octane that the gasoline matches in knock characteristics when compared by the procedure specified may be converted to performance numbers by a chart. The lean mixture rating together with the rich mixture rating can be used as a guide to the amount of knock-limited power that may be obtained in a full-scale engine under cruise (lean) and take-off (rich) conditions.

XI.2.4 It has been observed that when isopropyl alcohol (IPA) is added to a Grade 100, Grade 100LL, or Grade 100VLL aviation gasoline as a fuel system icing inhibitor, the antiknock rating of the fuel can be reduced. Since isopropyl alcohol is normally added in the field at the point of use, the operator is cautioned that performance numbers on the alcohol fuel blend may not meet specification minimums. Typical performance number reductions with addition of one volume % IPA has been 0.5 motor octave number on the lean rating and 3.0 to 3.5 performance number on the rich rating. Thus a Grade 100, 100LL, or 100VLL aviation gasoline rated in the knock test engines at the point of manufacture to be 99.5/130 octave/performance number might, with the addition of one volume % alcohol, be about 99/127 octave/performance number. At three volume %, the reductions are about 1.5 octave number and 7.5 performance number for lean and rich ratings, respectively. It should be noted that a survey conducted by the General Aviation Manufacturers Association failed to find field evidence or experience to suggest that these reductions have caused engine distress, that is, knocking or power loss at their...
recommended 1 % maximum level. On Grade 80 aviation gasoline, addition of the IPA additive can increase the octane rating.

X1.2.5 Knock Value, Lean Mixture Rating (Test Method D2700)—The specification parameter knock value, lean value mixture lists both "Motor Octane Number" (MON) and "Aviation Lean," as determined by Test Method D2700. Historically, aviation lean ratings were determined (from 1941 through 1970) by Test Method D614. An extensive comparison of National Exchange Group data from 1947 through 1964 established that motor octane numbers as determined by Test Methods D357 and D1948 could be converted to equivalent Test Method D614 ratings. A table to convert MON to the corresponding aviation lean rating was included in Test Method D2700, which was first issued in 1968 as a revision, consolidation and intended eventual replacement of Test Methods D357 (Withdrawn 1969), D614 (Withdrawn 1970), and D1948 (Withdrawn 1968). Currently "Aviation Lean" ratings are only determinable from the MON conversion table in Test Method D2700. However, the equivalent "Aviation Lean" rating is maintained as a specified parameter in Table 1 to ensure aircraft compliance with historical type certification data sheets.

X1.2.6 Rich Mixture Rating (Supercharge Test Method D909)—This test method uses a laboratory engine that is capable of being operated at varying air-fuel mixtures and through a range of supercharge manifold pressures. The rating of a fuel is determined by computing its knock-limited power with those for bracketing blends of reference fuels under standard operating conditions. The rating is made at the rich peak of the mixture response curve (about 0.11 fuel-air ratio) of the lower bracketing reference fuel.

X1.2.7 Tetraethyllead—Tetraethyllead offers the most economical means of providing high antiknock value for aviation gasoline. It is added to aviation gasoline in the form of a fluid which, in addition to tetraethyllead, contains an organic halide scavenger and an identifying blue dye. The scavenging agent is needed to keep the tetraethyllead combustion products volatile so that they will theoretically be completely discharged from the cylinder. Actually, lead compounds are deposited in the combustion chamber and some find their way into the lubricating oil. The products of combustion of tetraethyllead fluid are also known to be corrosive. Since deposition and corrosive tendencies are undesirable, the quantity of tetraethyllead in aviation gasoline is limited by specification commensurate with economic considerations.

X1.2.8 Dyes—The law provides that all fuels containing tetraethyllead must be dyed to denote the presence of the poisonous component. Colors are also used in aviation fuels to differentiate between grades. Service experience has indicated that only certain dyes and only certain amounts of dye can be tolerated without manifestation of induction system deposition.

X1.3 Fuel Metering and Aircraft Range

X1.3.1 Density—Density is a property of a fluid and is of significance in metering flow and in mass-volume relationships for most commercial transactions. It is particularly useful in empirical assessments of heating value when used with other parameters such as aniline point or distillation.

X1.3.2 Net Heat of Combustion—The net heat of combustion provides a knowledge of the amount of energy obtainable from a given fuel for the performance of useful work; in this instance, power. Aircraft design and operation are dependent upon the availability of a certain predetermined minimum amount of energy as heat. Consequently, a reduction in heat energy below this minimum is accompanied by an increase in fuel consumption with corresponding loss of range. Therefore, a minimum net heat of combustion requirement is incorporated in the specification. The determination of net heat of combustion is time consuming and difficult to conduct accurately. This led to the development and use of the aniline point and density relationship to estimate the heat of combustion of the fuel. This relationship is used along with the sulfur content of the fuel to obtain the net heat of combustion for the purposes of this specification. An alternative calculation, Test Method D3338, is based on calculations of aromatics content, density, volatility, and sulfur content. This test method may be preferred at refineries where all these values are normally obtained and the necessity to obtain the aniline point is avoided. The direct measurement method is normally used only as a referee method in cases of dispute.

X1.3.3 No great variation in density or heat of combustion occurs in modern aviation gasolines, since they depend on hydrocarbon composition that is already closely controlled by other specification properties.

X1.4 Carburetion and Fuel Vaporization

X1.4.1 In many spark-ignition aviation engines, the gasoline is metered in liquid form through the carburetor where it is mixed with air and vaporized before entering the supercharger from which the fuel-air mixture enters the cylinder of the engine. In other types of engines, the fuel may be metered directly into the supercharger, the cylinder, or the combustor. The volatility, the tendency to evaporate or change from a liquid to a gaseous state, is an extremely important characteristic of aviation fuel.

X1.4.2 Gasolines that vaporize too readily may boil in fuel lines or carburetors, particularly as altitude increases, and cause vapor lock with resultant stoppage of fuel flow to the engine. Conversely, fuels that do not completely vaporize may cause engine malfunctioning of other sorts. Therefore, a proper balance of the volatility of the various hydrocarbon components is essential to satisfactory performance of the finished fuel.

X1.4.3 Vapor Pressure—The vapor pressure of an aviation gasoline is the measure of the tendency of the more volatile components to evaporate. Experience has shown that fuels having a Reid vapor pressure no higher than 49 kPa will be free of vapor-locating tendencies under most conditions of aircraft usage. A research report is available.®

X1.4.4 Distillation—The relative proportions of all the hydrocarbon components of a gasoline are measured in terms

® Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report BR.020-116.
of volatility by the range of distillation temperatures. The method is empirical and useful in comparing fuels, but is not intended to separate or identify quantitatively the individual hydrocarbons present in the fuel.

X1.4.4.1 A maximum value is set on the 10% evaporated point to ensure ease of starting and a reasonable degree of flexibility during the warm-up period. To guard against too high a volatility that might lead to carburetor icing or vapor lock, or both, (also protected against by the vapor pressure test) a minimum value is set for the sum of the 10 and 50% evaporated points.

X1.4.4.2 A maximum value is specified for the 50% evaporated temperature to ensure average volatility sufficient to permit adequate evaporation of the fuel in the engine induction system. Insufficient evaporation may lead to loss of power.

X1.4.4.3 A maximum temperature is prescribed for the 90% evaporated point to prevent too much liquid fuel being delivered to the cylinders, resulting in power loss, and to prevent poor distribution to the various cylinders. Such a condition might lead to excessive leaness in some cylinders with consequent engine roughness, perhaps accompanied by knocking and damage to the engine. Lowered fuel economy and excessive dilution of the lubricating oil may result from too high a 90% evaporated point.

X1.4.4.4 A minimum value is stipulated for the 40% evaporated temperature in an effort to control, indirectly, specific gravity and, consequently, carburetor metering characteristics.

X1.4.4.5 A maximum is placed on the final boiling point (end point) which, together with the maximum prescribed for the 90% evaporated point, is used to prevent incorporation of excessively high boiling components in the fuel that may lead to maldistribution, spark plug fouling, power loss, lowered fuel economy, and lubricating oil dilution.

X1.4.4.6 The stipulation of a minimum recovery and a maximum loss in this specification in conjunction with the vapor pressure requirement is intended to protect against excessive losses by evaporation in storage, handling, and in the aircraft tank. It is also a check on the distillation test technique.

X1.4.4.7 A maximum value is specified for the distillation residue to prevent the inclusion of undesirable high-boiling components essentially impossible to burn in the combustion chamber, the presence of which may reflect the degree of care with which the product is refined or handled. The amount of residue along with the end point temperature can be used as an indication of contamination with high-boiling materials.

X1.5 Corrosion of Fuel System and Engine Parts

X1.5.1 Copper Strip—The requirement that gasoline must pass the copper strip corrosion test provides assurance that the product will not corrode the metal parts of fuel systems.

X1.5.2 Sulfur—Total sulfur content of aviation fuels is significant because the products of combustion of sulfur can cause corrosive wear of engine parts.

X1.6 Fluidity at Low Temperatures

X1.6.1 A freezing point requirement is specified to preclude solidification of any hydrocarbon components at extremely low temperatures with consequent interference with fuel flow to the engine.

X1.6.2 Fuel System Icing Inhibitor—Isopropyl alcohol (IPA), approved in 6.3.2.1, and diethyleneglycol monomethyl ether (DEGME), approved in 6.3.2.2, shall be in accordance with the requirements shown in Specification D4171.

X1.7 Fuel Cleanliness, Handling and Storage Stability

X1.7.1 Existent Gum—Gum is a non-volatile residue left by evaporation of fuel. The amount of gum present is an indication of the condition of the fuel at the time of use. Excessive quantities of gum are indicative of contamination of fuel by higher boiling oils or particulate matter and generally reflect poor fuel handling practices.

X1.7.2 Potential Gum—Fuel must be usable after storage for variable periods under a variety of climatic conditions. The potential gum test, which is an accelerated oxidation method, is used to estimate fuel stability in storage and the effectiveness of oxidation inhibitors. If the fuel is to be stored under relatively mild conditions for short periods, an oxidation period of 5 h is generally considered sufficient to indicate if the desired stability has been obtained, whereas a 16-h period is desirable to provide stability assurance for long periods and severe conditions, such as storage in tropical climates.

X1.7.3 Visible Lead Precipitate—The formation of a lead precipitate during the aging period of the potential gum test under the accelerated oxidation conditions used in this determination indicates a potential instability. Since even small amounts of insoluble material may foul the induction system and plug filters, it is necessary to place a limit on the amount of precipitate formed in this determination.

X1.7.4 Permissible Oxidation Inhibitors and Oxidation Inhibitor Content—Antioxidants are used to prevent the formation of gum in fuel during storage. The efficacy of a given inhibitor determined by the apparent oxidation stability of a fuel does not completely establish its suitability for use in an aircraft engine. Oxidation inhibitors have been found to contribute to excess induction system deposits; therefore, their acceptability for use must ultimately be determined in the full-scale aircraft engine.

X1.7.4.1 The chemical names of approved inhibitors and the maximum quantities permitted are shown in this specification.

X1.7.5 Water Reaction—The water reaction method provides a means of determining the presence of materials readily extractable by water or having a tendency to absorb water. When the fuel consists essentially of hydrocarbon components, there is no measurable change in the volume of the water layer.

X1.7.6 Electrical Conductivity—The generation of static electricity can create problems in the handling of aviation gasolines. Addition of a conductivity improver may be used as
an additional precaution to reduce the amount of static electrical charge present during fuel handling. See Guide D4865 for more information.

X1.7.7 Microbial Contamination—Uncontrolled microbial contamination in fuel systems may cause or contribute to a variety of problems including corrosion, odor, filter plugging, decreased stability, and deterioration of fuel/water separation characteristics. In addition to system component damage, off-specification fuel can result.

X1.7.8 Guide D469 provides personnel with limited microbiological background and an understanding of the symptoms, occurrence, and consequences of chronic microbial contamination. The guide also suggests means for detection and control. Biocides used in aviation fuels must follow engine and airframe manufacturers' approval guidelines.

X1.8 Miscellaneous Tests

X1.8.1 Aromatics Content—Low boiling aromatics, which are common constituents of aviation gasoline, are known to affect elastomers to a greater extent than other components in aviation gasoline. Although Specification D910 does not include an explicit maximum aromatic limit, other specification limits effectively restrict the aromatic content of aviation gasoline. Benzene is virtually excluded by the maximum freezing point of −58°C, while other aromatics are limited by the minimum heating value and the maximum distillation end point. Thus, the heating value limits tolune to about 24%. Xylenes have a slightly higher heating value and, therefore, would permit somewhat higher aromatic concentrations; however, their boiling points (above 138°C) limit their inclusion at levels not higher than 10%. Total aromatic levels above 25% in aviation gasoline are, therefore, extremely unlikely.

X1.9 General

X1.9.1 Further detailed information on the significance of all test methods relevant to aviation gasoline is provided in Manual MNI 1.9

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Manually on Significance of Tests for Petroleum Products, MNI 1, ASTM International.

SUMMARY OF CHANGES

Subcommittee D02.04 has identified the location of selected changes to this standard since the last issue (D910-07a) that may impact the use of this standard.

(I) Included provisions for Grade 100/130VLL (very low lead) aviation gasoline throughout the standard.

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