ASTM Aviation Gasoline Fuel Specifications - Beyond ASTM D910 and Leaded Fuels

ASTM D910 is the major specification covering Aviation Gasoline. ASTM D910 now has four grades: Grade 91, Grade 100LL, Grade 100 LL and Grade 100. (The grade 80/87 was removed from ASTM D910 to free up a dye color for possible use in an unleaded grade to aid in identification as it is anticipated that several unleaded avgas grades might come onto the market.) A UL91 grade has been added to ASTM D7547 and it is anticipated that the Grade 91 will now be removed from ASTM D910 freeing up the brown color and reducing ASTM D910 to three grades.

All four of the current grades in ASDTM D910 are leaded.

Grade 91
- 91.0 min octane by ASTM D2700
- 98 min octane by ADTM D909
- Lead g/L 0.56 max
- Dyed Brown

Grade 100VLL
- 100.0 min octane by ASTM D2700
- 130.0 Performance Number by ASTM D909
- Lead g/L 0.43 max
- Dyed Blue

Grade 100LL
- 100.0 min octane by ASTM D2700
- 130.0 Performance Number by ASTM D909
- Lead g/L 0.53 max
- Dyed Blue

Grade 100
- 100.0 min octane by ASTM D2700
- 130.0 Performance Number by ASTM D909
- Lead g/L 1.06 max
- Dyed Green

The industry has been under pressure to move away from these leaded grades and to make and sell unleaded aviation gasoline. The effort to safely move General Aviation over to unleaded aviation gasoline has shifted from industry efforts over to the Piston Aviation Fuel Initiative (PAFI) being led by Peter White of the FAA.

There are now four unleaded aviation gasoline specifications:

- ASTM D6227 “Standard Specification for Unleaded Aviation Gasoline Containing a Non-Hydrocarbon Component”
· ASTM D7719 “Standard Specification for High Aromatic Content Unleaded Hydrocarbon Aviation Gasoline”

· ASTM D7960 “Standard Specification for Unleaded Aviation Gasoline Test Fuel Containing a Non-hydrocarbon Component”

ASTM D6227 was originally issued in 1998 with the title “Standard Specification for Grade UL82 and UL87 Unleaded Aviation Gasoline”. But the name was changed in 2012 to better reflect that the fuel could contain ethers which are one way to meet the specifications octane requirements without the use of lead. While no deliberate addition of alcohols is allowed other than isopropyl alcohol used as a Fuel System Icing Inhibitor the aliphatic ethers can be added up to an oxygenate limit of 0.3 mass % oxygen maximum. Both the UL82 and UL87 are undyed and colorless. The specification was introduced as an aviation grade replacement for the automotive gasolines specified in many Autogas Supplemental Type Certificates issued since the early 1980’s. The FAA released Safety Awareness Information Bulletin (SAIB) No, CE-00-19R1 approving the use of ASTM D6227 82UL as an alternative for Autogas STC’s. This SAIB was released to registered owners and operators of airplanes approved for the use of Autogas and allow them to use the 82UL without requiring changes to the applicable airplane documentation. Additionally, the specification was developed to be able to make an aviation grade fuel from so called “normal” petroleum gasoline stocks rather than the specifically tailored stocks. (The stocks being used for 100 LL Avgas are specifically tailored and are iso-pentane, and high grade alkylate, toluene and lead plus a dye.)

ASTM D7547 “Standard Specification for Hydrocarbon Unleaded Aviation Gasoline” was introduced in 2009 and was done so at the behest of the U.S. military. As stated in the Scope of the specification it covers formulating specifications for purchases of aviation gasoline under contract and is intended primarily for use by purchasing agencies. The primary purchasing agency at that time being the Defense Energy Support Center (renamed in 2010 as the Defense Logistics Agency – Energy). The need for this specification was brought on by the increasing use of drone aircraft powered by the Rotax engine which was designed around unleaded gasoline with a MON of 91.0 minimum. Using the readily available 100LL with up to 0.56 gPb/l was causing severe spark plug fouling. Many of these drones were not being operated at full power but on long slow cruise missions in order to obtain high quality surveillance photographs, under these operating conditions not all the lead oxides were being removed from the combustion chamber and were building up on spark plugs.

With the exception of there being no lead and the octane being specified only by the MON value of 91.0 max the other requirements of ASTM D 7547 are the same as ASTM D910. There is a lead content specification of 0.013 g/l maximum which is taken from automotive gasoline specification where that level, based on extensive testing was considered the highest level of incidental contamination from general lead pick up as unleaded gasoline passed through previous infrastructure used for leaded motor gasoline. There is now a second grade in this specification UL 94 with a minimum Motor Octane Number of 94.0 by ASTM D2700. This grade was basically transferred into this specification from ASTM D7592 which was a test fuel. Upon completion of the transfer ASTM D7592 was withdrawn. Swift Fuels makes the UL94 and sells it as a replacement grade for to 100LL for use by lower-octane requirement piston engines that don’t require 100LL. Swift advertises that the UL94 is made with normal petroleum
stocks. See the web site for the map of locations where Swift sells UL94 Avgas. ([https://swiftfuels.com/fuel/unleaded-ul94-avgas/](https://swiftfuels.com/fuel/unleaded-ul94-avgas/))

**ASTM D7719 (Swift Fuel)** “Standard Specification for High Aromatic Content Unleaded Hydrocarbon Gasoline” is based on the high octane Swift fuel. See scope on ASTM D7719. This is for purchasing of a high octane unleaded fuel for testing purposes. It is a 102.2 minimum Motor Octane by ASTM D2700. Usually thought of as a mix of mesitylene and isopentane. The spec has been used to purchase fuels for submission to the UAT ARC Testing Process at the FAA W. J. Hughes Tech Center. This is the PAFFI test program. Costs of this fuel remain uncertain at this time. But could if approved under PAFFI find use. Much will depend on what the FAA decides, basis the PAFFI testing, and which aircraft can use the Swift fuel. A benzene limit has been added to ASTM D7719 of 0.1 mass pct. max.

There are reportedly problems with the compatibility between this Swift fuel and 100LL Avgas. The octanes tend to drop below an acceptable level in the mid-range of mixture volume percentages. The current leaded fuels are made up of alkanes and the lead works well with the alkanes giving a high Motor Octane Number. As you add the high aromatic fuels to the alkane leaded fuels the ability of the lead to give a high Motor Octane response drops away and somewhere in the 40 to 60pct range of high aromatic fuel inclusion in the blend you get a fuel with a lowered MON (so called incompatible fuels). Then as you move towards higher aromatic inclusions moving from the 60 % to a 100% so the aromatics take over and become predominant and the MON is restored to an acceptable level. To possibly ease some of these compatibility questions Swift has hinted at an ASTM meeting of introducing another fuel to this specification, it would be a UL100. They then changed this and said it may come under another test fuel specification and be called 100R. To date no research report has been issued to allow this proposal to go forward.

**ASTM D7960** “Standard Specification for Unleaded Aviation Gasoline Test Fuel Containing a Non-hydrocarbon Component.” This is an unleaded aviation gasoline specification being championed by Shell. The grade designation is UL 102 and it is a 102.5 minimum Motor Octane Number fuel. It is generally thought of as a blend of high octane alkylate and a range of aromatic amines and aromatic components. Previous references to “Non-hydrocarbon” components has been associated with the inclusion of ethers in a blend but here it is a reference to the aromatic amines.

### Table 1

<p>| Brief Outline of ASTM Specifications and Guides Being Used or Intended for Use in Looking for an Unleaded Aviation Gasoline – Replacing Avgas 100LL |
|---|---|---|---|
| <strong>ASTM Specification No.</strong> | <strong>Name</strong> | <strong>MON</strong> | <strong>Comments and Possible Future Application</strong> |
| ASTM D 910 | Specification for Aviation Gasoline | 100 Leaded | Contains only leaded fuels. Could be phased out but probably only very slowly. Grade 100 used where refiners can’t make the octane requirements of MON 100 Aviation Lean Rating without the use of higher lead levels than allowed in 100LL. The 100VLL is a lower lead version of 100LL. The Grade 91 may be withdrawn in the future leaving the three 100 grades. |</p>
<table>
<thead>
<tr>
<th>ASTM Specification No.</th>
<th>Name</th>
<th>MON</th>
<th>Comments and Possible Future Application (Some of these comments should be considered speculative)</th>
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</thead>
<tbody>
<tr>
<td>ASTM D7547</td>
<td>Specification for Unleaded Aviation Gasoline</td>
<td>91 and 94 Unleaded</td>
<td>Originally the 91 octane grade was used by the military purchasing agency for use in aircraft designed to operate on 91 MON unleaded fuel. The 94 MON unleaded grade is made and sold by Swift fuels and possibly others. Both grades are finding increased usage. Hjelmco 91/96 UL is a product that can be sold against the 91 grade. Hjelmco uses lean/rich MON numbers and so the product is similar to the 91 aviation grade. Aircraft/engine manufacturers have been making engines certified to run on 91 octane fuel and have issued approvals for the Hjelmco 91/96 and the Total UL91. Both fuels are available in Europe.</td>
</tr>
<tr>
<td>ASTM D7719</td>
<td>Specification for High Octane Unleaded Test Fuel</td>
<td>102.2 Unleaded</td>
<td>Swift Fuel. See scope on ASTM D7719. This is for purchasing of a high octane unleaded fuel for testing purposes. Usually thought of as a mix of mesitylene and isopentane and is a high aromatic content gasoline. The spec is being used to purchase fuels for submission to PAFI testing program.</td>
</tr>
<tr>
<td>ASTM D7960</td>
<td>Standard Specification for Unleaded Aviation Gasoline Test Fuel Containing a Non-hydrocarbon Component</td>
<td>102.5 Unleaded</td>
<td>This is an unleaded aviation gasoline specification being championed by Shell. Like ASTM D7719 this is a test fuel as explained in the scope. The Shell fuel is thought of as a high aromatic fuel with a range of aromatic amines and alkylate.</td>
</tr>
<tr>
<td>ASTM D6227</td>
<td>Specification for Unleaded Aviation Gasoline Containing a Non-Hydrocarbon Component</td>
<td>82.0 and 87.0 Unleaded</td>
<td>Loosely based on automotive gasoline. See write up in previous section to this table. Only for use in engines and associated aircraft that are specifically approved by the engine and aircraft manufacturers and certified by the National Certifying Agencies with Supplemental Type Certificates. Components containing ethers may be present but alcohols are specifically excluded.</td>
</tr>
<tr>
<td>New Fuel Testing Guide</td>
<td>Standard Guide for the Evaluation of New Fuels and New Fuel Additives for Use in Aviation Spark-ignition Engines and Associated Aircraft Installations</td>
<td></td>
<td>Very much a part of the UAT ARC recommendations and requirements to be met by prospective suppliers of new fuels before undertaking actual engine testing. Quite extensive and requires up-front capital to demonstrate meeting all the test requirements. There has been constant changes to this specification over the last 5 years – and it’s still a work in progress.</td>
</tr>
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Detonation Test Methods

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<tr>
<th>Method</th>
<th>Description</th>
<th>Purpose</th>
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<tr>
<td>ASTM D6424</td>
<td>Standard Practice for Octane Rating Naturally Aspirated Spark Ignition Aircraft Engines</td>
<td>Rates MON for PRF’s at specific points in engine operation</td>
</tr>
<tr>
<td></td>
<td>Put in place to be able to standardize test procedures for evaluating the octane rating of new fuels. It is for ground based octane rating for naturally aspirated spark ignition engines using primary reference fuels.</td>
<td></td>
</tr>
<tr>
<td>ASTM D6812</td>
<td>Standard Practice for Ground-Based Octane Rating Procedures for Turbocharged/Supercharged Spark Ignition Aircraft Engines</td>
<td>Collect data on knocking and conditions</td>
</tr>
<tr>
<td></td>
<td>Put in place to be able to standardize test procedures for evaluating the octane rating of new fuels. Similar to ASTM D6424 but this method is for ground based ratings of turbocharged/supercharged engines.</td>
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Table 1 Brief Outline of ASTM Specifications and Guides Being Used or Intended for Use in Looking for a Replacement Unleaded Aviation Gasoline

Other Fuels Not Covered By Specs

There are two other fuels of interest. One is the Afton-P66 fuel which is a blend of alkylate and Manganese Methcyclopentadienyl Manganese Tricarbonyl (MMT) and the other is GAMI’s G100UL Unleaded Aviation Fuel.

**Afton – P66 UL Avgas** There is no current specification on this fuel but Afton is developing a research report which they will ballot along with a specification at some time in the future. Afton has however issued two administrative ballots on their proposed fuel.

The scavenger chemistry is being deliberately obfuscated at this time and is considered proprietary. Intellectual Property data is being put in place and eventually information on the scavenger will be made public. Some scavengers will hurt and are detrimental to octane. It has been decided to stick with the so called “Scavenger B” for the time being.

In discussions with Zach McAfee of Afton he said getting the right scavenger and right amount is proving to be a challenge. A good scavenger that will not moderate the octane downwards will be one that tends to build up deposits in the combustion chamber. Unlike the ethylene dibromide scavenger in leaded fuel which is very volatile and exits the combustion chamber the scavenger for MMT is not volatile and tends to build up deposits. Afton have had discussions with the FAA on what would be acceptable to the FAA and to pilots on the time interval for the removal of spark plug deposits and cleaning interval for the plugs when operating on MMT. A 50 hours of engine operation might be an
acceptable limit to be sure combustion chambers don’t build up too much in the way of deposits. But to be safe the FAA has talked in terms of a 50 pct reduction on safety grounds, so that would be cleaning of spark plugs after every 25 hours of operation and probably not acceptable to aircraft owners. There has also been discussions with the transition team as the mechanics will all need to be retrained to understand the MMT deposits in terms of their morphology and color which are substantially different from lead. They are working with Champion to design plugs for MMT rather than lead – not sure yet where this work is leading but Champion has assured Afton that the design of the plug can make a difference in deposit build up. The deposits with MMT while not volatile are friable and will break off and exit the combustion chamber. (Does not sound great to me as this sounds like an increase in the particulate burden in the air – may not be toxic exactly but you are still going to be breathing more particulate.) The scavenger currently being used is called Scavenger B and it will decrease octane in manifolds at low temperature and Afton and Philips are working to lower the additive content and beef up the alkylate octane level (This is where P66 comes in by supplying a high octane alkylate).

General Aviation Modifications Inc. (GAMI) G100UL Unleaded Aviation Fuel

The GAMI fuel is made up of 1,3,5 trimethyl benzene (also known as mesitylene) plus meta toluide and a limited concentration of amines. The GAMI fuel was not accepted for further evaluation in PAFI and so GAMI decide to pursue an STC. While GAMI claims the components could be easily made in a refinery that may not be the case in reality and the components could be expensive. Solid estimates of costs seem unresolved at this time.

There is still a task force on the ASTM Sub Committee J books but there has not been a meeting of the task force in several semesters. Some years back (Dec 2015?) at an ASTM meeting the Chairman of the Avgas subcommittee "suggested" to Tim Roehl of General Aviation Modifications Inc. (GAMI) that they hold a "genuine" task force meeting and come up with a ballot item for GAMI’s G100UL Unleaded Aviation Fuel or disband. (The background behind this stems from some "disagreements" between GAMI (George Braly) and the FAA Tech Center and a feeling that GAMI might be using ASTM and the Tech Center to try to legitimize their fuel without actually coming up with an acceptable unleaded avgas standard available to the public.)

Information on GAMI’s testing procedure is given in their web site:
http://www.gami.com/g100ul/g100ul.php

There appears to still be a lot of ongoing issues and politicking. My understanding, which I have not been able to corroborate, is that GAMI has not pursued having their fuel included in the PAFI program. Instead they have sought an STC covering their fuel and they have patented the materials in their fuel.

The On-Going Conundrum of Taking the Lead Out of Aviation Gasoline

The 1990 amendments to the US Clean Air Act (CAA) mandated lead phase out for all “non-road” engines and vehicles. It stated that after 1992 engines could not be manufactured that required leaded fuels. In addition in 1996 no leaded fuel was to be sold commercially. These amendments to the CAA
were responsible for initiating the effort towards the development of an unleaded fuel to replace Avgas 100LL.

After careful review of the legislative record behind the CAA, it was determined that aircraft emissions were regulated under a separate title of the Act, and that aircraft were not considered by Congress to be “non-road” vehicles. At the same time it was recognized that the Environmental Protection Agency (EPA) held the authority to regulate lead emissions from aircraft stemming from the original Clean Air Act in 1970. The aviation industry (i.e. General Aviation Manufacturers Association (GAMA), Aircraft Owners and Pilots Association (AOPA), Experimental Aircraft Association (EAA) the FAA etc.) approached the EPA asking for a reprieve from the regulations to allow time for research and development toward finding an unleaded replacement for 100LL.

To that end, an industry group consisting of the FAA, Original Equipment Manufacturers (OEMs) and aviation consumer groups visited producers to demonstrate the desire for, and requested the development of, an unleaded 100 octane aviation gasoline (i.e., UL100 Avgas). Simple solutions that were thought to hold promise, such as replacing TEL with more toluene (the option adopted in moving from Grade 100/130 normal lead to 100/130 low lead, referred to as 100LL) or attempting the use of other metal additives, failed. Moreover, the use of readily available octane boosting oxygenated streams used in motor gasoline (Mogas) at the time (e.g., Methyl tertiary butyl ether (MTBE), Ethyl tertiary butyl ether (ETBE), Tertiary amyl methyl ether (TAME) and Ethanol) also failed to produce the necessary octane performance. It was then recognized that the problem was more complex than initially anticipated, and that a significant effort would be required to remove lead from aviation gasoline and maintain safe octane levels for the existing aircraft fleet.

Parallel to this initial effort, the industry was attempting to determine the aircraft fleet octane requirements. In order to make this determination two ASTM methods needed to be developed, providing standard practices for octane rating aircraft engines (i.e., ASTM D6424 & ASTM D6812). One method applies to naturally aspirated spark ignition aircraft engines while the other applies to turbocharged engine octane rating.

Despite extensive effort going back to the late 1970’s and the acceleration in developments after 1990, no unleaded replacement aviation gasoline fuel has been found and approved that provides adequate and comparable safety and performance to 100LL. Work on this important issue continues and is now moving forwards through the FAA with efforts to study and develop a suitable unleaded alternative to 100LL. The FAA and EPA were very much brought into the research and development effort as a result of a petition from the Friends of the Earth (FOE) asking for lead to be removed from aviation gasoline.

The tetraethyl lead (TEL) added to the avgas as required by ASTM D910 is necessary in order to achieve the required octane for safe operations in many aircraft. The combustion products of TEL are exhausted to the atmosphere increasing the burden of lead found in the environment. These lead combustion products are neurotoxins that have been shown to harm neurological development, especially in children. The environmental group, Friends of the Earth (FOE) petitioned the Environmental Protection Agency (EPA) in 2006 to issue:

An endangerment finding for lead emissions from piston powered aircraft or
Study the health and environmental impacts of aircraft lead emissions, if there was insufficient information to support an endangerment finding.
The FOE stated in their petition that lead emissions from General Aviation cause or contribute to air pollution that may reasonably be anticipated to endanger public health and welfare.

On July 8, 2012 the EPA issued a final decision to the FOE petition basically stating it did not have the data to support an endangerment finding. Then in March 2013 the US District Court granted the EPA a summary judgment to dispose of the suit brought by the FOE including an understanding that the EPA would continue doing testing of lead levels at airports with significant General Aviation (GA) operations.

Entirely separate from the Friends of the Earth petition but under a federal court order to set a new standard by 15 October 2008, the EPA cut the acceptable limits for atmospheric lead from the previous standard of 1.5 \( \mu g/m^3 \) to 0.15 \( \mu g/m^3 \) (or 150 ng/m\(^3\)). This was the first change in the standard since 1978 and represents an order of magnitude reduction over previous lead levels. The EPA also identified avgas as one of the most “significant sources of lead”. They also committed to a yearlong study of 17 airports with heavy General Aviation traffic. Contrary to their statement that avgas was a significant source of lead, the final results from the EPA’s modelling study at the Santa Monica Airport shows that off-airport lead levels are below the current 150 ng/m\(^3\). And 15 of the 17 airports monitored during the yearlong study have shown lead emissions well below the current US National Ambient Air Quality Standard (NAAQS) for lead. Only the airports at San Carlos CA and McCellan-Palomar Airport in Carlsbad CA showed data exceeding the national standard. Concern was registered over the placement chosen for the lead sensors at these two airports. The sensors were moved to less direct trafficked areas at these two airports and in these new locations the lead levels were not above the NAAQS.

Nevertheless, there is a recognition that lead should be removed from avgas and in May 2012 the Federal Aviation Administration (FAA) issued a report from the FAA Unleaded Avgas Transition Aviation Rulemaking Committee (UAT ARC). The EPA was a partner to the recommendations in UAT ARC report. Basically the report emphasizes the need for safety: that safety for piston aircraft operations; their owners; and the far reaching economic impacts will over-ride any EPA wishes to see lead summarily removed from Avgas. This committee consulting with experts from many parts of the industry put a plan together to replace leaded avgas with an unleaded alternative fuel within eleven years. A part of this transition is the creation of the Piston Aviation Fuels Initiative (PAFI) with the goal of facilitating the development and deployment of a suitable and high enough octane fuel that will have the least impact on the General Aviation fleet and distribution system. The evaluation process will focus on a fuel’s production and distribution infrastructure, toxicology, and overall cost of aircraft operations.

Through PAFI the FAA has now embarked on the search for an unleaded avgas to replace 100LL. On July 1, 2014 the FAA closed its submission for fuels under the PAFI plan. Nine fuels were submitted from five different groups, including Afton Chemical Company, Avgas LLC, Shell Oil, Swift Fuels, and a consortium made up of BP, TOTAL, and Hjelmco. From the original nine submitted fuels the FAA selected three candidate fuels which underwent preliminary testing at the FAA’s William J Hughes Technical Center. Results of this testing led to just two fuels going forward for extensive aircraft and engine testing both on the ground and in the air. Congress is supporting this program with an initial amount of $6 million per fiscal year. If all went well a new unleaded aviation gasoline was supposed to be deployed in 2018. At the December 2017 ASTM meeting in Houston Peter White advised that they are behind schedule and the testing and evaluation of results will not be completed and a report issued until 2019. The replacement for 100LL with depend on availability and costs as well as technical feasibility and on avoiding the octane incompatibility with 100LL to allow for a seamless distribution. Some comments
have been made that the higher horsepower engines like the Piper Navajo will not be able to operate on the new fuel and will need to have engine replacement/changes. There were statements made at the ASTM meeting to the effect that the FAA is looking at strengthening the wording that will go into the Federal Register to allow the FAA to make a onetime declaration on what aircraft model and engine combinations will be certified to fly on the new fuel. There will be some aircraft that will not be allowed to fly on the new fuel.

Apart from the fuel aspect there are some excellent parts to the UAT ARC that may allow for engine modifications and changes. In particular changing over to modern engines capable of running on 94UL but with performance “similar” to that of current aircraft operating on 100LL. Under this scenario, gradually 100LL will move out of the market as older high performance aircraft are retired or re-engined. OEM’s are working on making engines that can operate on UL 94 and have similar performance and be suitable for re-engining of some specific aircraft that were originally certified to run on 100LL. The OEM’s may follow Continental’s lead. Continental has reduced the compression on an engine and fitted it with Full Authority Digital Engine Control (FADEC) systems so it can operate on 94 MON unleaded with performance similar to the original older engine(s) requiring 100LL. However, with this approach the conundrum of supplying at least two grades of compatible aviation gasoline, at least for a period of time, will still need to be resolved.

**Overview and Concluding Remarks**

There are approximately 167,000 piston-engine aircraft in the United States and a total of 230,000 worldwide that primarily rely on the currently available Avgas 100LL as defined in ASTM D910 “Standard Specification for Aviation Gasoline”. The 100LL specification has been developed iteratively over many years using the ASTM consensus process. The limits for all the critical properties have been vetted and agreed to only after considerable debate and understanding of aircraft and engine operations and always with a view to safety of flight. All grades of gasoline in ASTM D910 are currently leaded but a considerable research effort is being headed up by the FAA through the PAFI program to come up with an unleaded alternative to 100 LL. ASTM will continue as the main organization setting the specifications for Avgas, based on safety of flight for these new and alternative replacement unleaded fuels.

ASTM members are not expecting there to be any specification put in place on the books until the FAA completes its work in 2019 and even then it seems unlikely there will be any ultra-quick moves to see ASTM D910 100LL removed from the market. It will be a slow and deliberate transition.

Updated January 2018