
**Figure 1.** Hot day fuel testing required by the FAA under Part 23. The FAA required "back-to-back" comparison of unleaded avgas verses traditional 100LL for vapor lock testing, even though both fuels have the same vapor pressure value. Both fuels performed exactly the same during extensive testing with 110 degree (F) fuel in the wing tanks, and during climbs to 25,000 feet and including engine shut downs and "cool off" periods while the aircraft glided down from 25,000 to 17,000 feet.

# GAMI's G100UL® Unleaded Avgas

## An Update

By George Braly, GAMI

In November of 2009, Tim Roehl and I were returning from the AOPA Summit in Florida. We used the cross-country time in N36TN to discuss the future of avgas. At the AOPA Summit there had been a lot of "heated talk" about the EPA and a possible ban on leaded avgas. Because GAMI had built the Carl Goulet Memorial Engine Test Facility, we had the ability to do comprehensive engine and detonation testing required to obtain the FAA's approval of a new aviation gasoline. We decided to see what we could develop.

Early in the process, we did some hard thinking and set out the design criteria for a future unleaded avgas. Those included:

1. *Detonation* – as good as existing 100 MON 100LL
2. *Producible with good economics* – The new fuel needed to be mostly made from components that are readily available from the existing refinery infrastructure so that the resulting fuel was "close" to the pricing on 100LL, recognizing that "close" is not a very precise term.
3. *Fungible* – You have to be able to mix a new fuel with existing 100LL in order to undergo a "graceful" transition to the new unleaded era of aviation gasoline.
4. *Chemically Compatible* – no worse adverse chemical degradation with airframe and engine "wetted" parts than with 100LL
5. *Transparent* – The pilot should not be able to detect which fuel is being used, absent sensitive instrumentation.

Seven years later, GAMI is getting close to its first STC for its unleaded avgas, which we have designated "G100UL."

In the interim, the FAA decided to create a government program to assist in the approval and deployment of a new unleaded avgas. This process started with an Aviation Research Committee (ARC) in the summer of 2011 and that extended process ended up resulting in 2013 with the creation of the Piston Aviation Fuel Initiative (PAFI) project. For a lot of reasons, GAMI elected to not participate in the PAFI process. One of the primary reasons was that in order to do so, GAMI would have essentially been required to start over with the certification process and we had already made a lot of progress, including conducting our first 150-hour on-aircraft endurance test.

Today's PAFI program is shrouded in a lot of secrecy because of claims of intellectual property and an associated confidentiality requirement by the two industry participants that remain in the program (Swift Fuel and Shell Oil Co.). Some information regarding the testing of those fuels has apparently leaked out. It is not our purpose here to discuss that, but if you are interested, AVweb has recently reported on the subject. See "Is Shell's Replacement Fuel Coming Up Short?", published October 30, 2016.

Some of GAMI's milestone accomplishments in the effort to obtain a "fleet wide" STC for its G100UL avgas include the following:

a. *First ever* FAA approved Part 23 airframe hot day/ climb / climb cooling/ vapor lock/ high altitude performance test in a high-compression, turbocharged, high-performance general aviation aircraft on an unleaded avgas (2012). It took about a year to get the final approval for the test plan. It took 30 days to then get ready and conduct the test. Four FAA engineers and project managers came to Ada, Oklahoma, to personally witness that testing. (**Figure 1**) This was required in spite of G100UL having the same vapor pressure limitations as 100LL, which, in our opinion, should have been adequate substantiation. The tests showed there was no difference between G100UL and 100LL.

b. A hundred and fifty hours on-aircraft engine and airframe durability test with G100UL. Embry-Riddle Aeronautical University did that testing using test fuel made by GAMI. God bless them! Embry-Riddle is one of the very few entities that has tried to help in any way, whatsoever. This included dimensional inspection of the relevant engine components prior to and after the 150 hours testing. There were no discrepancies noted and these test results have been accepted as "approved" data by the FAA.

c. *First ever* FAA approved test results for a fleet wide unleaded avgas certification approval for "material compatibility." It took about a year to get that test plan approved and then about eight months to do that test and get the results approved. This included a wide selection of representative airframe and engine parts that were subjected to long-term fluid contact with the G100UL and 100LL under simulated operating conditions. Think of multiple new and used fuel bladders, fuel lines, O-rings, gaskets, seals, fuel pumps, etc. All tested. We even tested a 60-year-old, "new-out-of-the-box" fuel bladder that was in someone's inventory!

d. First ever FAA approved test plan for conducting detonation testing for fleet wide approval of a new unleaded avgas. It took about 19 months to get that test plan approved. We are now just beginning that testing, which will hopefully only take about 30 days to accomplish. This was required in spite of the fact that G100UL meets the same minimum MON (Motor Octane Number) as 100LL at 99.6 MON. This process also involved an FAA "Issue Paper" technical review of the test methods to be used. GAMI was able to substantiate our test methods using modern instrumentation, and document that we were testing detonation at the same detonation intensity levels as were previously used for OEM engine certification.

## What Remains To Be Done?

1. Finish the detonation testing now underway;
2. Conduct some further minor on-aircraft validation testing on some additional aircraft;

3. Conduct one further 150-hour engine block test on our test stand. We have done several of those in the past, so that is not difficult or complex or new – just expensive and time consuming.

When we finish the first item in the remaining to do list, we should get an initial STC that covers a number of aircraft and engines. When we finish the second and third items, we should, according to the FAA agreed to project specific certification plan, then obtain a "fleet wide" STC for GAMI's unleaded avgas.

In the process of getting the FAA approval for the detonation test plan, GAMI ended up having to do a lot of fundamental R & D [Research and Development] work. That testing resulted in some genuinely new discoveries with respect to comparative detonation testing of unleaded verses leaded aviation gasoline fuel chemistries. These discoveries at this late stage are truly astonishing given that the automotive and aircraft piston engine world has been doing extensive formal detonation testing since WWI.

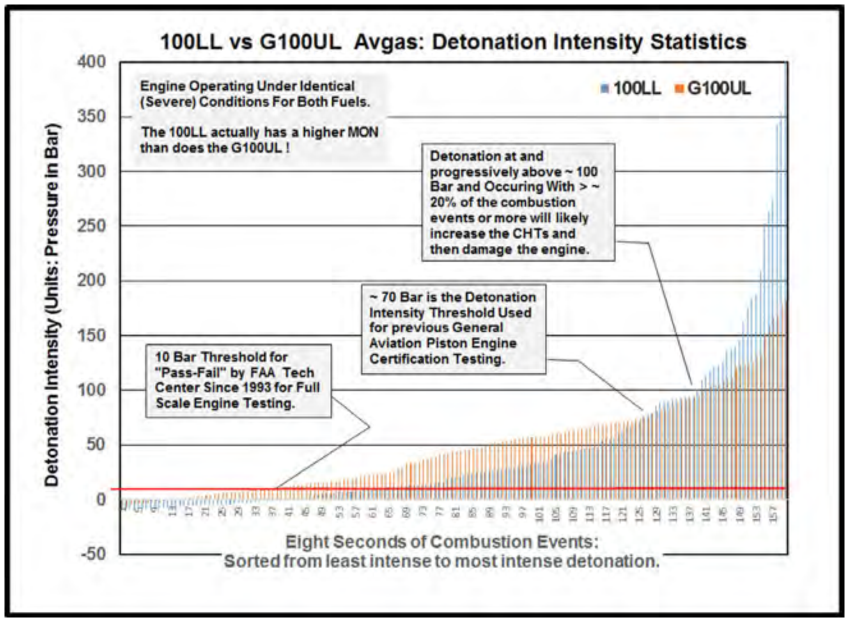


**Figure 2.** Graph plots 8 seconds of continuous combustion events for Cylinder 5, for two different fuel chemistries and with their respective detonation intensities calculated, sorted by intensity, and displayed in the bar graph. If you had to choose, which fuel would you rather use if your engine was operating under those severe conditions?

## Detonation

During past (1950 through the 1990s) OEM engine certifications involving what is now an estimated 98+ percent of the current general aviation piston engine fleet, detonation was measured with accelerometers attached to the cylinder heads using a WWII era instrument analyzer made by Sperry. In 1993 the FAA R&D facility in Atlantic City started to use in-cylinder pressure transducers to measure and quantify the intensity and occurrence rate of the detonating combustion events. That new technology has the ability to quantify the magnitude of very low and ***operationally insignificant*** levels of combustion event anomalies. As a result, the FAA decided to use those very low intensity level combustion events as the basis for a set of "pass-fail" criteria for testing unleaded fuels on full scale piston aircraft engine.

However, the MON (motor octane number) as measured by the refinery in the laboratory uses a test method (single cylinder variable compression ratio engine) developed back in the 1930s. The detonation intensity threshold used for the ubiquitous MON & RON (research octane number) that we see at the local gas station fuel pump is an order of magnitude more "severe" or "intense" than the "pass-fail" intensity threshold later selected for use by the FAA and the ASTM avgas members for all of the full-scale aircraft engine unleaded fuel testing done from 1993 to the present.

Because the FAA was doing comparison testing between new unleaded fuels and traditional 100LL, the fact that the FAA was using different (more recent or "modern") threshold intensity and occurrence rate criteria for detonation pass-fail determinations appeared rather reasonable. However, during the first few years of that testing, the FAA and industry (ASTM avgas committee members) came to the universal conclusion that "for some reason" unleaded fuels that tested in the laboratory at 102 or 103 MON would not perform as well as a leaded fuel with a MON of 100 – on ***full scale general aviation piston engines*** – using the new FAA R&D engine detonation test methodology.

Note the words above: ***for some reason***. Nobody ever asked why.

To the best of our knowledge, until 2013 when GAMI undertook the fundamental R&D on this issue, nobody had *ever* properly made any attempt to correlate the knock intensity threshold that was used in the actual OEM engine certification of our general aviation engines and the knock intensity thresholds used in the more recent FAA R&D testing. Why not? Because everyone (including GAMI) made an assumption. An assumption that was never articulated, but was inherent to the whole process. That previously unstated assumption:

> "We are going to assume that comparing different fuel chemistry detonation results by using a test criteria that is very different from the laboratory (MON) and certification test methods is 'valid' because we assume that doing 'comparisons' of new candidate fuels to traditional 100LL at the very low intensity test thresholds will be valid because, along with other factors , we are willing *to assume that all of the different possible fuel chemistries will have the same statistical distribution of knocking combustion event intensities, and therefore, it does not make any difference at which detonation intensity level we elect to use to make 'pass-fail' comparisons between 100LL and any possible new unleaded avgas."*

At GAMI, we saw ongoing anomalies in the data over the years that caused us to question the "universal consensus" held by those performing the testing at the FAA's Engine Test Facility and some other industry representatives that unleaded fuels need to have MON values 2-3 MON points higher than leaded fuels in order to perform the same on full-scale aircraft engines as 100LL.

So GAMI devised a simple preliminary test. We tested two fuels: a traditional 100LL and G100UL. Both fuels had the same laboratory MON value. What we did was collect about eight seconds of continuous high speed (50 kHz sample rate) detonation data

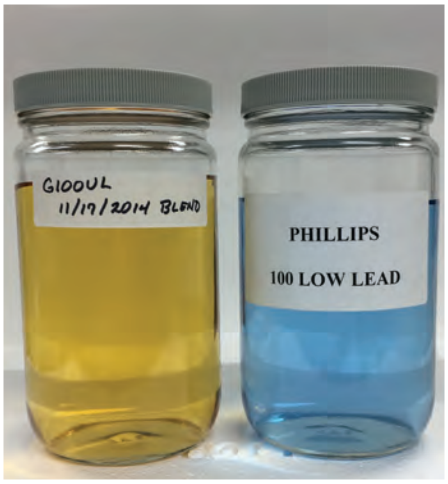


**Figure 3.** G100UL® has no added dye for coloring, like 100LL. Other than the color and a different "olfactory" quality, the pilot will likely not be able to appreciate the difference. One thing pilots with good instrumentation may appreciate is that when operating with LOP mixtures in cruise, the fuel flow will be about 0.3 GPH lower in your Bonanza – with the engine making the same horsepower.

under identical operating conditions for each fuel. The operating conditions were severe enough to ensure the fuels would in fact be detonating at some significant level. **See Figure 2**.

We calculated the detonation intensity (using the FAA's R&D test method algorithm) for each of the combustion events for one specific cylinder that was detonating the most severely within that eight second window. Then we sorted that eight seconds worth of combustion event data from least intense to most intense in magnitude of detonation intensity. The result is plotted in the graph shown in **Figure 2**. We have since confirmed those initial results by measuring tens of thousands of consecutive combustion events on leaded and unleaded avgas fuel chemistries.

The previously unstated assumption turned out to be false.

As is now evident, different fuel chemistries have dramatically different statistical distributions of the occurrence rate and magnitudes of their detonating combustion events. This leads one to an appreciation of the significance of "damage relevant" vs. "non-damage relevant" knock intensities as a part of the quality assessment of the fuel.

## Progress

When we showed this new data to the FAA, they required us to go through a yearlong "Issue Paper" process to document what we had found. At the end of that intensive process, and to their credit, the FAA approved the data and the associated detonation test methods we had documented. GAMI is now in the process of doing the final detonation testing required to obtain its first unleaded fuel STC.

Early on, GAMI (with the gracious help of Embry-Riddle) accomplished a 150 hour on-aircraft engine durability test on a Lycoming engine. We have one more 150 hour engine durability test to complete (on a big bore Continental engine). At that point GAMI will write the final reports and we should then be able to obtain a fleet-wide STC for an unleaded avgas that will function transparently to the pilots for all of the general aviation fleet of engines. Your future avgas may well look like that shown in **Figure 3**.

## Some Observations

This process has been unbelievably frustrating and difficult. GAMI has had virtually no support, aid, or assistance from any outside sources in the general aviation industry, other than the greatly appreciated help from Embry-Riddle in performing the 150 hour on-aircraft engine durability testing.

We are confident this unleaded fuel "works." It does not require "special" or unique starting procedures for cold weather operations. It does not require that the carburetor or fuel injection system be adjusted. It should be fully able to be mixed in the fuel tank in any ratio with 100LL.

If you have any questions, contact *gwbraly@gami.com* or *troehl@gami.com.*