Pelican's Perch #83: The Shell Report

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by John Deakin
Columnist

Pelican's Perch

The Shell company recently published their Shell Aviation Tech Talk #15 (990 Kb Adobe PDF file) and distributed it to all pilots in Australia and New Zealand. I'm getting a lot of questions from readers there, and from graduates of our seminar.

The bulk of the report is an excellent treatise on detonation and pre-ignition, well worth reading.

Unfortunately, sprinkled throughout that fine report are a few bits of "common knowledge" that have proven to be not true, or what we call "old wives tales" (OWTs). Most involve mixture settings, with recommendations to run 50¡ÆF rich of peak (ROP) exhaust gas temperature (EGT). Most readers will nod their heads as they skim past these, and as little as 10 years ago, I would have, too; "Everybody knows that!"

But 10 years of looking at hard data from one of the most sophisticated engine test stands in the world, and using the data and information in my own well-instrumented airplane (Bonanza with an IO-550 and Tornado Alley Turbonormalizer) has changed my outlook dramatically.

About the Author ...

John Deakin is a 36,000-hour pilot who worked his way up the aviation food chain via charter, corporate, and cargo flying; spent five years in Southeast Asia with Air America; 33 years with Japan Airlines, mostly as a 747 captain; and is now flying Gulfstream IVs full time as a charter pilot. He also flies his own V35 Bonanza and is very active in the warbird and vintage aircraft scene, flying the C-46, C-131, DC-3, F8F Bearcat, Constellation, B-29, and others.

All the rest of John's "Pelican Perch" columns are available here.

Specifically, a few of the minor points in the report repeat some OWTs about mixtures that have developed in the last 50 years, and which are not supported by the old engineering manuals, or by more recent data from the test facility. We've been working hard for 10 years to dispel these, with some success.

I have contacted the author, a very pleasant fellow who seems very interested, and who wrote a long email in support of his position.

I repeat for emphasis, it *is* a fine report -- on detonation and pre-ignition. The author did not have the advantage of "modern data," and fell into the near-universal trap of believing the OWTs. In general, I commend Shell and the author for the bulk of the report.

Let me work my way through it, commenting as I go.

Mogas Malignity

> *"I recently had a email from an operator who reported engine damage and that he suspected the octane quality of the fuel he had been using. The damage can be seen in the accompanying photographs."*

The more I see of mogas (auto gas) use, the less I like it. I think Shell has taken an "international attitude" for the benefit of all the good folks who are using mogas in what must be considered "bush flying" (Australian Outback, Africa, etc.). My interest is more in the U.S. GA piston world, where the use of mogas is extremely limited and declining, due to the "stuff" they're putting in it, and the difficulty in finding it, transporting it, and using it.

Some pretty heavy-duty testing on the test stand has proven beyond a doubt that in a "conforming" engine (one meeting all specs) and using "conforming" fuel (normal-quality 100LL), it is all but impossible to force detonation in these normally-aspirated engines. Detonation can be induced deliberately in the big turbocharged engines (like mine), but to do it, we must run somewhere above 85 percent of rated power, and run the CHTs up to extreme levels. By that I mean within 30 to 50 degrees of the factory redline.

Heavy detonation can lead to bad things -- quickly. Often it will lead to spark plug damage and the associated pre-ignition that the Shell Report describes so well, and then the pre-ignition (not the detonation) ends up destroying the cylinder (and possibly the engine). But by and large, a careful review of the history reveals that detonation itself is rarely if ever responsible for most engine problems and failures.

The Shell Report makes it very clear that pre-ignition is a different process, and is most likely the real culprit in most of the horror stories. (The report has an excellent example).

> *"The principle damage can be seen to be an area of pitting in the cylinder head between the spark plug hole and the valve seats. The operator suspected either pre-ignition or detonation was the cause of the damage. Pre-ignition and detonation are totally different phenomena; pre-ignition occurs when there are hot spot deposits within the combustion space to act as an ignition source, whereas detonation is the spontaneous auto ignition of the unburned end gas through an increase in its thermal energy."*

Detonation Details

Something I've learned in only the last five years or so is that there are levels of detonation! I was taught 50 years ago that detonation was the rapid burning (explosion) of *all* of the unburned end gas at once. Not so. It turns out that there is "light," "medium," and "heavy," detonation with mathematical formulas to calculate and identify them. It is also possible for detonation to occur on a single combustion event out of many, or on several combustion events, and then cease, with perfectly normal events in between. When those intermittent detonation events start occurring more frequently, problems develop rapidly.

This was one of many "rude awakenings" I've had while looking at *data*, as

opposed to OWTs.

We've also found that occasional "light" detonation is probably harmless, and may even be beneficial, for it appears to clean out deposits very well. Intermittent medium detonation is not much of a concern, but probably shouldn't be tolerated for long periods of time. It's too close to "the edge."

An analogy, if I may. Detonation is a bit like walking up to the rim of the Grand Canyon, with no fence. You're fine, as long as you don't fall over. But just a little bit closer, and it will quickly become a very bad day. Light detonation itself is probably harmless, but you're standing on the edge of that cliff. Medium detonation ... well, you get the point.

> *"Detonation damage tends to manifest itself around the circumference of the piston, as this is where the unburned end gas is. By the very nature of detonation, it is the end gas is where the problem first starts and it is where the damage is typically seen. As detonation is caused by the progression of the flame, and the expansion of the gas behind the flame putting energy into the unburned air/fuel mix, then damage is typically not found in the area where the flame first starts. Damage around the spark plug is not characteristic of detonation."*

That is a fine example of what I mean by the report being so good.

> *"**PRE-IGNITION***
>
> *Now this is more probable, with the spark plug being a source. If, for some reason, the spark plug is running hot, then it could itself present a source of ignition prior to the spark and result in the damage shown. The area that appears to be damaged most in these photographs is the area between the spark plug and exhaust port. This is where the cylinder head runs hottest, as it is difficult to cool this area (lack of metal to conduct heat away, poor cooling fin area around that area and the exhaust port is perpetually dealing with hot gas)."*

Good stuff!

> *"Cylinder head cracking is common in this area in engines which are cooled too rapidly because of the poor thermal path from this area, and it is common to see weld repairs between the exhaust port and one of the spark plug holes as a result. So we know that this area runs hot and this further supports the pre-ignition supposition."*

We are deeply suspicious of any of the "shock cooling" theories, with an awful lot of data that suggests it's largely an artifact of aviation mythology (another term for OWT). But it certainly makes good sense to be gentle with power changes. We look at Bob Hoover, who would go from full power to instant feather, then right back out of feather to full power again, several times during his Shrike Commander act, several shows a day, and many shows a year. His engines routinely made full TBO without problems. Sky-diving airplanes, flight school airplanes, all routinely go to TBO, given decent treatment otherwise. All of those seem to suffer a LOT of "shock cooling" with complete aplomb.

(We think they do so well because: 1) They are flown frequently; and 2) They are never operated in our "Red Box" -- see below.)

> *"The next question is why might the spark plug running excessively hot? In this case the spark plug insulation was damaged, offering one of two failure mechanisms. Firstly, the plug insulation might have been the primary failure, presenting a hot centre electrode, which could then have caused the secondary pre-ignition damage. Alternatively the plug itself may have run too hot, creating a pre-ignition source, which damaged the cylinder head and subsequently shattered the plug insulation."*

Be still, my heart! "Right on!" I cannot tell you how much it pleases me to see a major organization putting out such good information! We teach that if a spark plug is dropped more than an inch, throw it away. In fact, I usually go on to advise clamping it in a big vise, and using a large hammer to beat the electrodes to death, so that some cheap airline pilot won't try to put it in another engine. (Yes, I'm a recovering airline pilot, so I know.)

Leaning Legends

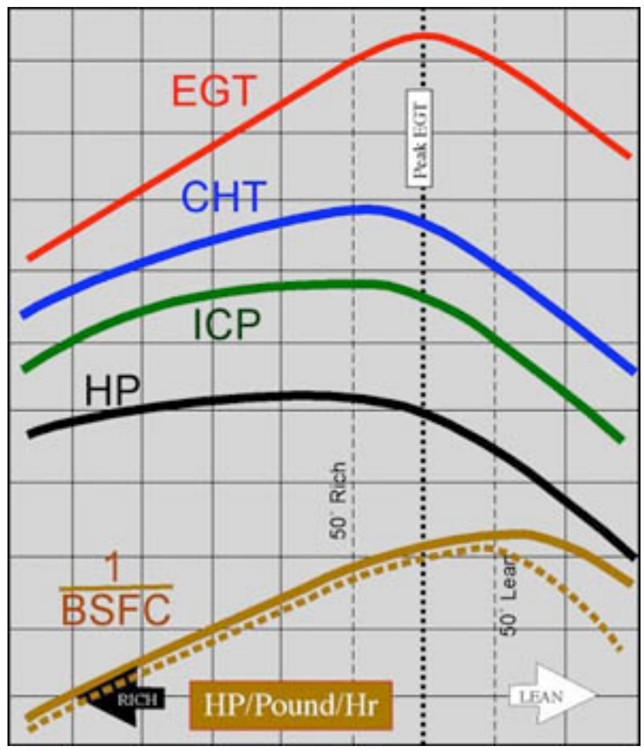
> *"The next factor that can make an engine run too hot is excessive leaning of the fuel mixture."*

Uh, oh. This line got my attention, and that of a number of readers in Australia and New Zealand!

> *"Leaning increases combustion temperatures ..."*

This is a major fallacy (once again, one that I believed myself until about 10 years ago). The factories say this, the FAA knowledge tests still say it, and "everyone knows it." But, consider ...

Here is a wonderful chart, found in the back of Teledyne Continental Motors (TCM) "Installation and Operation" manual for the IO-550 engine. Similar charts are found in most of the "big-bore" manuals, although the most recent of them now omit a lot of very good data, including this chart. To this, we have added color, and a fifth trace for "ICP" which is internal combustion pressure as measured from pressure transducers in the engines on the test stand.



Piston engine combustion measurements.

This chart was produced at 25" of manifold pressure, and 2500 RPM. At those settings, the mixture is leaned from rich (on the left) to lean (on the right).

Until about 10 years ago, very, very few of these engines would run smoothly at all if leaned to peak EGT or leaner. We always thought this was due to poor air distribution, but it turned out to be poor fuel distribution, solved by [GAMIjector](#) fuel injectors. As a result, very, very few people even knew of "lean of peak" (LOP) and the right side of that chart was effectively a dark area similar to the old world maps at the edge of the flat Earth, with notations of "There Be Dragons Here."

Until recently, "rich" was to the left side of the chart, and "lean" was at 50ºF ROP.

Folks, 50ºF rich of peak EGT is *not* lean! It is a *rich mixture*. Not as rich as full rich, but rich, nonetheless!

No one even seemed to know there was another area to the right, which is truly lean.

GAMI's fuel injector technology opened up the whole spectrum shown by that chart, and it has become the centerpiece of our course.

When your mechanic says, "Too lean," he means the area just rich of peak EGT -- which isn't lean at all! It's still a rich mixture, but it is indeed "too lean." ("Not rich enough" is a better way to say it.) This is the common trap the author of the Shell Tech Talk fell into, and this goes to the very heart of the myths we've been trying to dispel. First, we need to get the terminology straight: Peak EGT ("stoichiometric," for the engineers) is neither rich nor lean, but *all* mixtures rich of that are rich mixtures (ROP), and *all* mixtures lean of that -- and *only* mixtures lean of peak -- are lean mixtures (LOP).

Lovingly Lean

If the engine will operate smoothly LOP, a number of good things happen, chief among them being a drop in CHT and ICP (see chart), and less stress on all parts of the engine.

The most critical parameter is peak ICP, which is directly driven by, and commensurate with, CHT at about 40ºF ROP. We teach not to use more than 60 or 65 percent power at this mixture setting on the TCM engines. (Lycomings may tolerate slightly higher power settings at this mixture.)

Moving away from peak ICP/CHT in either direction will cool things off and cause less stress on the engine. This has been measured on the test stand. In fact, going about 250ºF ROP EGT in a normally-aspirated engine will allow production of 100 percent power, which we use for takeoffs. Going to about 90ºF LEAN of peak EGT will cause a much slower and later peak pressure (and CHT), and will cost about 15 percent in HP.

Turning this around, we recommend operation (normally aspirated) at wide-open throttle, 2500 to 2700 RPM and 70º - 90º LOP at sea level, to 20º LOP at 8,000 feet or so. If you leave the throttle wide open, power is effectively modulated by altitude. At sea level, that's 85 percent power! That's for normally aspirated engines and turbonormalized engines only. This is not for turbocharged engines capable of greater-than-normal sea level manifold pressure. For those, we suggest about 32" MP instead of "full throttle."

In my turbonormalized engine (with sea level MP to FL220), I run 31" and 2500 to 2700 RPM in cruise at all altitudes to 25,000 feet, for 85 percent power all the time, but *lean of peak only*. The engine loves it, no signs of distress now at 700 hours, and many folks are doing the same thing through and well beyond TBO.

(Using the same techniques, the big Wright R-3350 on the Connies and DC-7s routinely went to 3,600 hour TBOs.)

> "*First of all, leaning should not be performed at any altitude at power settings above 75 percent power as this threatens the risk of detonation; however, the reduction in air density above 6,000 feet generally means that a normally aspirated engine cannot make more than 75 percent above this altitude and so leaning is generally possible at all throttle settings above 6,000 feet in normally aspirated engines*."

This widely-held belief is true only with the limited spectrum I mention above (rich side only), and not even fully true there. We teach leaning from a couple of thousand feet above sea level on up. The wonderful TCM Altitude Compensating Pump on many TCM engines does the same thing automatically.

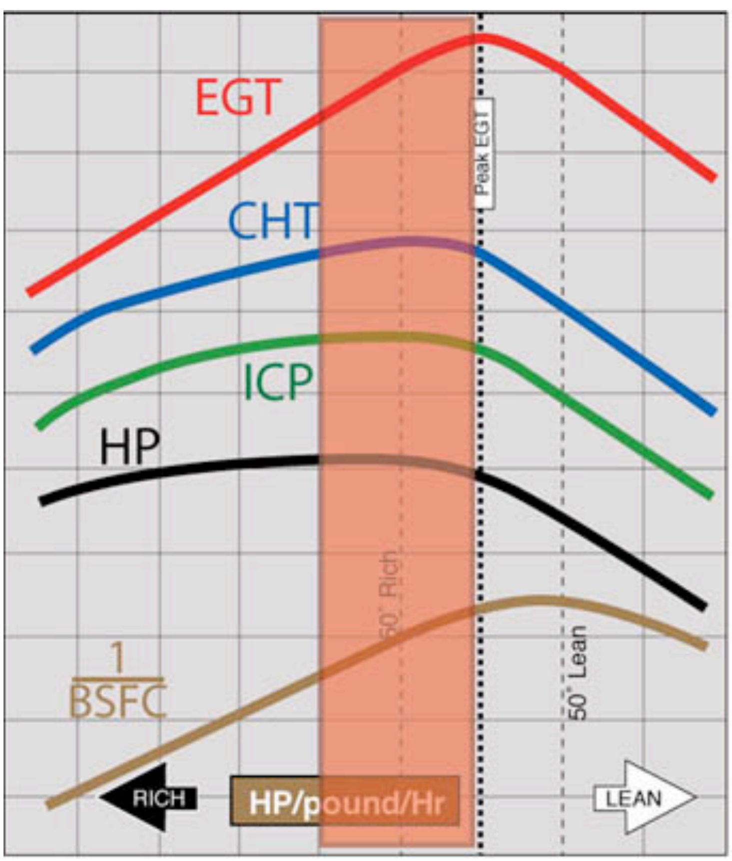
> *"I have seen a lot of people leaning to peak EGT and beyond, but I much prefer to see pilots lean only to 50ºF on the rich side of peak for reasons that I will not cover here, but perhaps is an area that we can cover in a future edition of Tech Talk."*

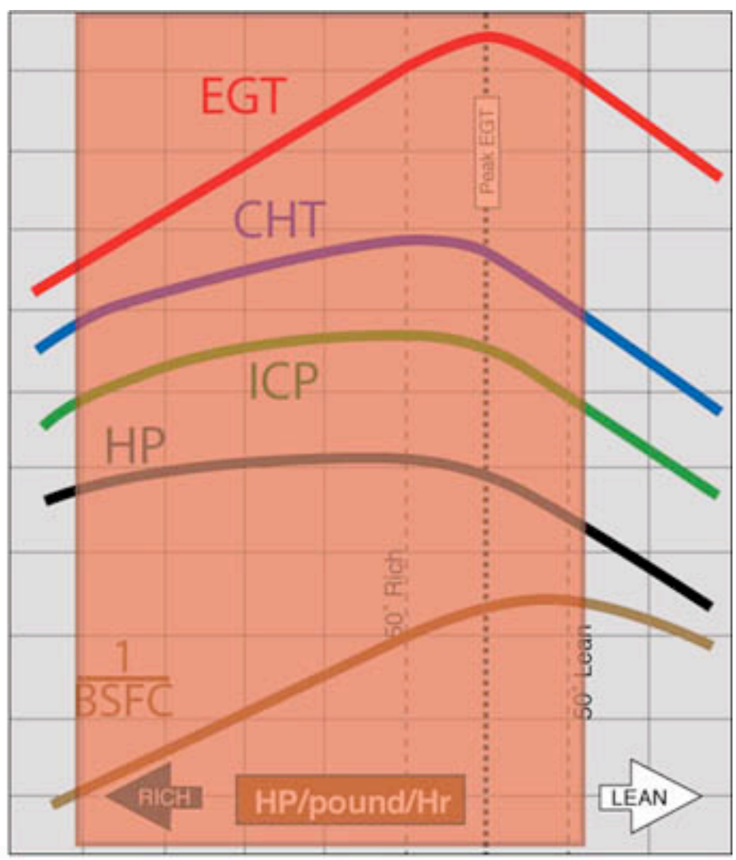
I hope the author (and Shell) will do a future article, correcting some of these inaccuracies.

I might add that what we're doing is not new. It was done years ago in the piston airline fleet, and heavily documented, using Brake Mean Effective Pressure (BMEP) -- essentially torque -- not EGT. There are roughly 400 million hours of highly successful operation on the big radials operating with a "10-percent drop" on the BMEP (lean of peak power). Whether using BMEP or EGT, the end result is the same combustion event.

Ruthlessly Rich

As you can see from the chart above, 50ºF ROP is the worst possible place to operate from the standpoints of temperature (CHT) and pressure (ICP). That mixture causes the highest CHTs, and the highest ICPs. We think you can do it safely at 60 percent or maybe 65 percent power, but not much more. If you will operate *richer* or *leaner* from that point, you are safe in making more power. At 250ºF ROP, you're safe with 100 percent power. If you'll run 90ºF LOP, you're safe at 85 percent power. For simplicity, we teach a "red box" centered on 50ºF ROP. It's a little skinny red box at 65 percent, and a great big fat one at 85 percent.





The "Red Box" danger zone for mixture settings at 65% power (left) and 80% power (right). For power settings between these two, the danger zone is correspondingly sized. At 60% power or less, there is no danger zone; you can set any mixture you like.

> *"This is particularly significant if operating above 65 percent power without specialised engine instrumentation. Also of note, when leaning an engine, is that the cylinder head temperature (CHT) is actually a more important marker than EGT, even though this temperature lags the EGT by some margin. If the CHT's are redlined then the mixture should be enriched to cool the head, regardless of what the EGT is saying."*

That's one way to do it, and I hope it's done long before reaching redline! Another way is to *lean more*, well over on the lean side! It works wonderfully well.

Also, a word about redlines. Factory redlines are intended to be "momentary only." We have a lot of recorded data where CHT has risen to the redline, usually due to an ongoing series of pre-ignition events. On those events that go beyond the factory redline, damage is inevitable. For those where the CHT is *promptly* controlled and brought back down, we seldom see damage to the cylinders. However, the spark plugs are often damaged, and should always be changed even if no damage is evident.

But that doesn't mean we can operate for long periods at high CHT! We prefer to treat 420ºF as an absolute, "do something right now" limit, with 400ºF as the point at which the engine monitor will show an alarm, and 380ºF or less as the nominal target for regular use. Those numbers are all for the TCM engines, and again, Lycomings may tolerate slightly higher temperatures, possibly due to more robust casting.

> *"Finally, are the spark plugs torqued up correctly with a new copper washer each time they are replaced?"*

Wonderful point! Too many are improperly torqued, as are fuel injectors!

> *"Most pilots are unaware that the majority of the heat transfer from a plug is through the gasket and seal area and so a good thermal contact in these areas is essential. Too often do you see copper washers being re-used when changing spark plugs, without a thought to either replacement or at least annealing the old washers to soften them. Used, hard washers result in a poor thermal contact and can lead to spark plugs overheating and pre-ignition damage within the engine.*
>
> *If the temperature management of the engine is adequate and the spark plugs were suitable and fitted properly, then this implies that the plug damage may have occurred first, but why?*
>
> ***PLUG DAMAGE***
>
> *Of course, one obvious way of damaging a spark plug is through mishandling before it even reaches the engine. If you do ever drop a spark plug, particularly onto a hard surface such as the floor, you should always replace it, even if there are no obvious signs of cracking on the insulator. Spark plugs can easily be damaged and it is far better to replace a plug than risk catastrophic engine damage due to failure of the plug insulation after assembly."*

This is more good stuff! It is really refreshing to see this kind of important information being directly disseminated by people who inherently speak with authority.

But I wish they'd stopped there!

Not So Shocking Cooling

> *"Another common cause of plug damage is through rapid cycling of the engine temperature -- power off descents after cruise, or excessive leaning, which rapidly increases exhaust gas temperature (EGT), are typical scenarios. As we have covered before, Lycoming recommend that the rate of change of cylinder head temperature should not exceed 50ºF per minute."*

The data suggests otherwise, as I mentioned above. We know of no data that supports the popular concept of "shock cooling." I am unaware of any hard data that supports the 50ºF per minutes "limit." On the other hand, one has to work pretty hard to get a 50ºF degree per minute change in the CHT! I think some have transposed this CHT change to EGT, erroneously adding it to their self-imposed "limits."

One pilot I know used to recommend not reducing manifold pressure any faster than 1" every *two minutes!* Now *that* is "Fear of Shock Cooling," and utterly ridiculous.

We agree with Shell that damaged spark plugs cause the vast majority of the pre-ignition events, and we think helicoil tangs (improper installation) may be a cause, too. Old fables exist that "deposits" might be one possible cause, but we don't see any real evidence of that. We can't fully discount it, but it just doesn't make sense. We do know that a bit of light detonation will clean out deposits very quickly.

Author's Response

On Dec. 14, 2006, the author replied to me, and the rest of the quotes are from that email:

> *"As for the advice of running 50ºF deg ROP, I think that this is safe practice for those operating at 65 percent power or more ..."*

This was the line that got my attention the most. This is exactly backwards. 50ºF ROP is safe enough at 65 percent or *less*. If setting any more power, then you should be *richer* or *leaner*. Look again at the first graph in this article: If you really want the highest possible CHT, the highest possible ICP, and the greatest stress on the engine for any given manifold pressure and RPM, then 40ºF to 50ºF ROP is your choice. However, it is well-appreciated in the engineering world that heat and pressure are the enemies of metal.

> *"... with engines that have not got engine instrumentation that includes individual EGT and CHT monitoring."*

There's an interesting point in this. Most people say, "I wouldn't operate LOP without a good monitor." We reverse that, and say "Running ROP is the more critical operation, and if anything demands an engine monitor, ROP operation is it."

Think about this. Suppose you are running a high power setting (climb, for example) while well ROP, and one fuel injector fouls. That will drive that cylinder to higher CHT (and ICP), and it may well detonate, damage a spark plug, and pre-ignition may occur.

If there is no monitor, you won't know it unless the single factory probe happens to be on that cylinder. Your first indication will be roughness after pre-ignition has eaten a hole in the piston and oil is pumping out the breather from over-pressure in the crankcase. Too late. An engine monitor would have saved the day.

On the other hand, if the engine is being operated LOP at 85 percent power and one injector fouls, that cylinder will go very lean (no harm), and will lose so much power the engine will run rough (harmlessly), telling the pilot there is a problem. With no instrumentation at all!

> "*Leaning decreases flame speed ...*"

Not so fast. You must identify where you start leaning, and where you stop! If you start at 50ºF ROP (40ºF is more technically correct, but never mind), then moving the mixture knob in *either direction* will decrease the speed of the flame front. Put another way, the fastest flame front of all is at 40ºF or 50ºF ROP.

> "*... but it also increases flame temperature up to the stoichiometric limit*."

Similar comment. The bulk temperature of the combustion gasses is highest at 40ºF ROP, and drops on both sides, including that area between peak CHT and peak EGT! Yes, the CHT goes down while the EGT goes up (see the chart above).

EGT Isn't The End of the (Combustion) Story

The fact is, EGT is *not* a good reflection of combustion temperature at all. It is more an indication of *when* the combustion occurs relative to top dead center or valve opening. In fact, if you lean enough, to something around 150ºF LOP, just before combustion ceases entirely, the EGT will *rise* briefly, as the very slowly-burning combustion event continues until the exhaust valve starts to open! This little oddity drove us nuts when we first saw it. (As an aside, diesel engines have very high peak pressures and temperatures, but tend to have lower EGTs than spark-fired engines.)

> "*Further leaning beyond stoichiometric will, of course, decrease the overall combustion temperature, but the slow flame speed may in fact increase temperatures later in the engine cycle*."

We know of no temperatures that will actually increase as the mixture is leaned past peak. Even the above artifact is not a case of higher temperatures, except at the EGT probe.

> "*For the point of the article, I felt that mentioning the fact that EGT temperatures will ultimately reduce with decreasing mixture strength was a detail that was not needed and it was sufficient to highlight that leaning is the most common cause of increases in CHT that could cause the type of thermal*

distress that was under discussion.

I do accept that leaning beyond stoichiometric can reduce EGT, but it can also result in flame speeds slow enough to thermally distress valves, especially if using highly aromatic, or alcohol-containing fuels such as some Mogas blends."

I'm unaware of any data to support this very common OWT, which is contrary to old engineering data from the heyday of piston engine development, and currently available hard data.

"*This thermal stress, and resultant reduction in of valve creep life, is not always picked up on a single point EGT gauge commonly fitted to most engines. There are a couple of reasons for this: intake harmonics commonly result in uneven mixture distribution meaning that the single point probe is not necessarily detecting the worst-case cylinder and, furthermore, hot gases at the valve face can cool rapidly before reaching the EGT sender therefore masking the problem. By inference, the use of multi-cylinder EGT probes placed close to the valve, operation on Avgas and the proper execution quite complex leaning procedures (covered quite well in Lycoming's publication SSP 700A) are the only safe way to lean beyond peak EGT without compromising valve creep life or running near the engine's detonation boundary. As a general case I feel it is safer for most people, with standard instrumentation, to be leaning to 50ºF rich of peak EGT.*"

Please look at this again in light of the above. The data simply doesn't support this. The problem with sub-standard octane is very simply that people don't adjust the spark timing to compensate for the change in flame front speed. This all started from a very old SAE report that mentioned valve-seat distress when using lower octane fuel, but they tested all octanes at the same spark timing. The report was all about the changes with different octanes and in this, it was well done. The valve damage was a footnote!

"*Furthermore, there is the question of detonation resistance. I need, in these articles, to be cognisant of the fact that not all operators are using Avgas as we would like. Many pilots use Mogas which is controlled for RON, but has widely varying MON values. As aviation engines typically display an Octane Index that is heavily (although not entirely) MON dependent, some engines may already be operating close to their detonation boundaries using some Mogas supplies. Of course, leaning the air / fuel ratio increases an engine's Octane Index demand (we have seen an average increase of 2 Octane Numbers is required for each 1.0 increase of the air-fuel ratio) and, considering the general case, it is impossible to know each engine's demand in the RON and MON spectrum, nor the corresponding Octane Index availability if the fuel in use is Mogas. In some cases Mogas may allow leaning beyond peak EGT and in other cases, even in those applications where Mogas is approved, it may not. Therefore I feel that, combining these factors, 50ºF rich of peak is generically a safer practice.*"

You were doing fine with that paragraph, until that last line! Regardless of octane, 50ºF (or 40ºF) ROP EGT is the worst possible mixture setting at any power setting. It is tolerable at 60 percent or less (maybe 65 percent), but not above. Even at 60 percent power, 40ºF ROP is still the mixture setting that produces the highest possible temperature and pressure in the cylinder. There are excellent methods of producing the same power with less stress.

There are wonderful comments about monitors. The one on my airplane is an absolute no-go item, for it's *my money* in that engine. We have far too much data that shows the incredible value of these instruments, where pilots either ignored the monitor and suffered the consequences, or followed it, and saved their engine, their airplane, and perhaps their lives.

> *"If operating at lower power levels 60 percent or below, the flame temperature and engine's octane demand are much reduced and it may be possible to safely operate Lean of Peak without individual cylinder monitoring. However, most pilots operate at, or above, 65 percent power in the cruise and it is in this region that I feel 50ºF Rich of Peak is a safer general practice."*

Exactly backwards. Please retract this.

If you AVweb readers learn nothing else from this article, understand that at all high (above 60 to 65 percent) power settings, under all conditions, 40ºF to 50ºF ROP is the mixture setting that results in the highest heat, pressure and stress for any given MP/RPM, and the greatest likelihood of detonation and/or pre-ignition. The engine will tolerate this mixture setting well only when running below about 60 to 65 percent power.

If you must run ROP, run rich enough.

Be careful up there!

More from AVweb's Pelican is available here.