Pelican's Perch #84: Don't Set Mixture with CHT

April 4, 2007

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Columnist

Pelican's Perch

There seem to be a growing number of people who think that a cylinder head temperature (CHT) of 380 °F is a universally good target to use for setting the mixture.

Folks, it just ain't so.

It may work some of the time on some engines, but it's a long way from universal, and I'd like to tell you why.

At least one engine may have required a premature overhaul because of this issue, and there is at least one seminar speaker who advocates this as a "simpler technique." That approach to "simpler" ends up creating some serious problems in many common situations.

Installation Differences

Absolute numbers are tricky. By "absolute" I mean the raw data numbers you see on your engine monitor for CHT, exhaust gas temperature (EGT) and turbine inlet temperature (TIT). Under completely normal conditions, EGT and CHT can be very different from cylinder to cylinder on the same engine, and from engine to engine, even of the same make and model, and even when all probes are installed exactly the same. TIT can also vary a lot from engine to engine. Even if you know what is "normal" for your own engine, in-flight conditions can vary so widely that using a fixed CHT number like 380 °F can be hazardous to the health of your engine.

Small differences in EGT/TIT probe placement, both along the exhaust pipe and radially, can make a significant difference in absolute numbers. Even if probe placement is "perfect," exhaust flow can come out of the cylinders differently, and can be affected by pressure pulses from other exhaust streams in the same manifold.

CHT sensors can be the older, spark-plug-gasket type, or the newer "bayonet" probes screwed into the

About the Author ...

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

cylinder head. Both types may exist in the same engine, and the spark-plug-gasket types usually run as much as 50 ºF hotter, because that part of the cylinder is hotter. CHT probes can be influenced to some degree by local cooling airflows, by nearby baffling or lack thereof, and by radiant heat from nearby hot components.

General Aviation Modifications (GAMI) has placed test probes all around the circumference of a cylinder head and found variations of as much as 150 °F, probably from the difference in airflow and cooling air temperature on the "front" side, compared to the "back" side.

GAMI and Tornado Alley Turbo (TAT) have a *lot* of data from the test stand on the IO-360, IO-470, IO-550, and IO-550TN ("TurboNormalized"), and several big Lycomings, including the "bad boys" ... the Lycoming TIO-540AE2A (Piper Mirage) and TIO-540J2BD (Piper Navajo) engines. These engines are generally in perfect running order, very well baffled, and exquisitely controlled. They still show significant differences cylinder-to-cylinder on the same engine. However, if engines are carefully installed in identical engine installations in identical airframes with identical instrumentation, they do routinely exhibit rather uniform patterns of CHTs and EGTs when comparing one *engine* to another under those types of controlled conditions.

Limits

I may have contributed to this confusion myself with my comments about the "insane" factory CHT limits (460 °F for TCM, 475 °F or 500 °F for Lycomings), and further commenting that 420 °F is a "better" redline, and then adding to that concept by asserting that 400 °F is a good setting for the "warning" on the engine monitor, and 380 °F as a "good target." If that last one (380 °F) was taken to be a universal "proper setting" under all conditions, I'm sorry. I didn't mean it that way.

Engine monitor

Let me try to clear this up.

The very high factory limits are not really "insane" if they are well understood. They are absolute limits to which the engines are tested for limited periods of time during certification. They're based on sound engineering, but they were never intended for continuous field operation. Our data suggests that if CHTs rise to the factory limits, and are promptly controlled and brought back down, there will probably be no significant engine damage. (Probably a good idea to install new spark plugs, though.) If the engine exceeds those limits, damage is likely. How much damage? That will be related to how bad the over-temperature is and how long it lasts. We have seen engines that went to 510 or 515 °F with no serious effect, but other engines that went to 525 or 530 °F and sustained significant damage in a short period of time.

A lot of the problems with these over-temp conditions are related to damage to spark plugs, which can quickly lead to bad stuff like pre-ignition. Bottom line: It all gets worse with increased temperature and the time spent at high temperatures. You may even get away with operating near those factory limits if you've lost one engine on a twin and must abuse the other one for a few minutes just to survive. But it's pretty clear that operation beyond those limits may very soon lead to a lot less power out of the running engine! Very high CHTs (but under red line) at very high power settings with appropriately full rich mixtures should not lead to detonation in a "conforming" engine (all parameters within spec), but it is really hard on the engines if those conditions last for extended periods.

These certification limits are derived from conforming factory engines, on a factory test stand, with everything pretty well controlled and monitored. When that same engine is installed in an airplane, the results may not be as satisfying. One area that concerns us is that many cylinder installations create large temperature differentials around the circumference of the cylinder. This can lead to the cylinder going out-of-round, and this will cause "scuffing" as the still-round piston is sliding up and down in a slightly out-of-round cylinder. That, in turn, can lead to a rapid build-up of CHT (we call it a "thermal runaway"), making the situation worse, leading to detonation and/or preignition. (Calling it a "snowball effect" seem inappropriate somehow, but "heatball" doesn't make sense, either.) Once this thermal runaway begins, it will not stop unless the pilot takes aggressive action (full rich, boost pump on, power back, as needed).

While we have seen the out-of-round condition start a thermal runaway as low as 410 to 415 °F, that is rather unusual. As a "best judgment," we like to consider 420 °F as a normal upper limit on CHTs. In short, 420 °F becomes our "do something, right now" redline. There are a number of other factors and considerations that go into that judgment call, but they are beyond the scope of this column.

Oops, we just used 420 °F, an absolute number! Is it valid for all engines? Maybe not, but in the absence of specific information to the contrary about a specific installation, it is -- in our judgment -- a good solid and appropriate number to use as an upper boundary.

To put it yet another way, it is not the 420 °F that hurts. If you see 400 to 420 °F during the last few thousand feet of climb, it's not going to hurt a thing – as long as it doesn't start rising in the classic runaway.

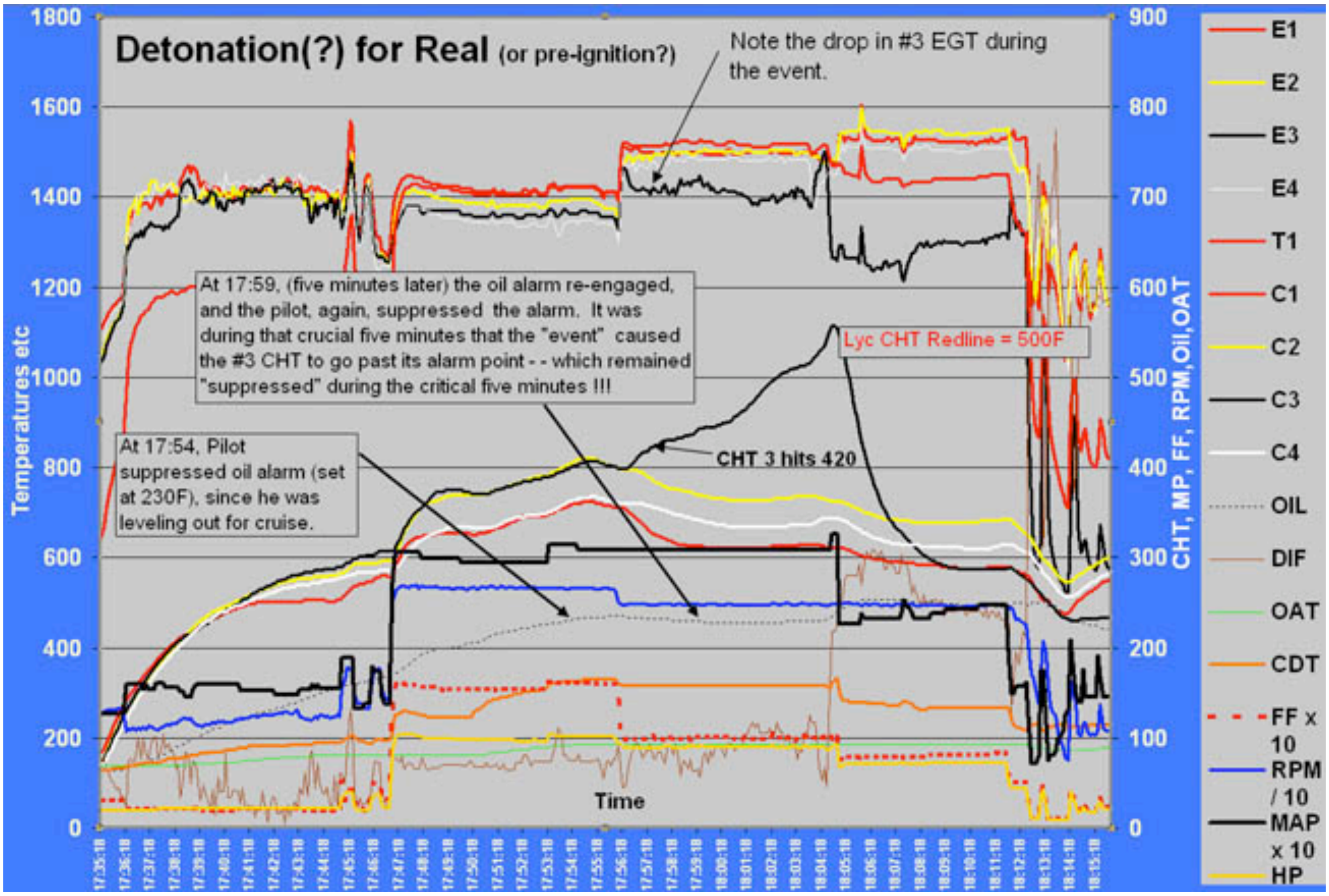
The considerations that go into this 420 °F number really don't depend in any way on ambient conditions; it's the metallurgy, in this instance.

If we want to keep the CHT below 420 °F, then we should probably set our engine monitors to alarm somewhere down around 400 °F. This gives us plenty of time to spot the (often too subtle) warning, to think about it, and take action.

Becoming Inured To Warnings

The next consideration is that we never want alarms to be so frequent that we might become accustomed to them, and not pay attention one day when it's important. A lot of engines will approach 400 °F in the climb, or with mishandling (low airspeed, for example). So here's where we say, "If your monitor is set to alarm at 400 °F, then use 380 °F as your target maximum." Don't let constant alarms inure you to them!

Here's one of my favorite examples. It's not an issue of setting mixture by CHT, but is beautifully illustrative of a number of points:

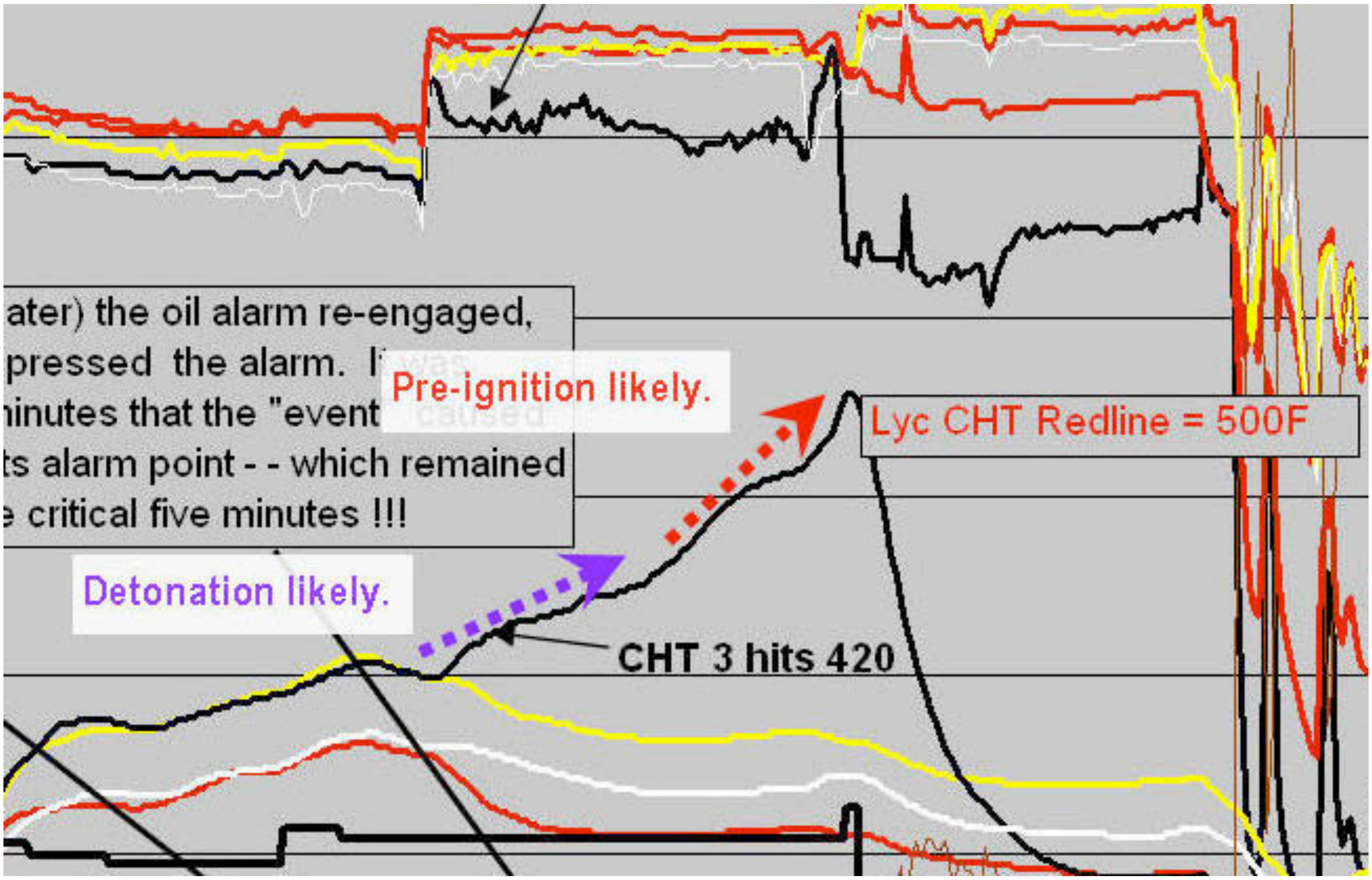


Engine Monitor Plot -- Runaway CHT. (Click here for larger version -- 280 KB.)

This pilot was getting oil temperatures of 230 °F on nearly every climb, and had become accustomed to just suppressing the alarm without worrying about it much.

On this flight, he got the usual alarm at 17:54 and suppressed it. "Oh, just that pesky oil temperature, again." Fair enough, most of us would do the same, although he might have found out why the oil temperature was going so high, all the time, and fixed it. Or set the alarm for 240 °F to avoid the nuisance alarms. All Monday-morning quarterbacking, of course; I'd have probably fallen into the same trap.

On this particular monitor, that suppressing the alarm disarms *all* alarms for five full minutes. Of course nothing else could go wrong during those five minutes, right? Guess again, and think of Murphy's Laws.



Runaway CHT plot -- excerpt showing detonation and preignition.

At 17:56:30 (two and a half minutes into the "no alarms" period), the #3 CHT started rising rapidly, probably preignition from a damaged spark plug. At 17:57:54, the CHT hit 420 °F, its alarm point. But the alarms were still suppressed. Internally, the monitor was yelling, "CHT! CHT! CHT!" but no one could see it.

Meanwhile, the oil temperature peaked at 236 °F and started back down slowly. Exactly five minutes after canceling the alarm, the time expired, the alarm reset itself, finding both an out-of-bounds oil temperature, and an out-of-bounds CHT. I don't know which one was displayed on the monitor.

Again, the pilot suppressed the alarm, still thinking a slightly elevated oil temperature was his only problem. He'd become accustomed to the oil temperature issue, and was accustomed to hitting the suppress button a couple of times, until it came down again.

The CHT continued its rise to 554 °F with no alarm. Five minutes after the second reset, the engine monitor woke up, discovered the high CHT, and the alarm activated. This time it showed the CHT, and the pilot almost instantly pulled the MP back to 23" (from 30.9), killing the preignition event. Well done, but too late to save the engine.

To repeat: Use 380 °F to avoid nuisance warnings at 400 °F and set your warning to 400 °F so you have time, precious time, to take action before reaching 420 °F, so that you don't get end up where you really don't want to be on CHTs.

Now here's the disconnect. This is *not* a blanket suggestion that it's OK to run all these engines at 380 °F CHT all the time. These issues up to this point have largely been related to material properties of the cylinders (metallurgy).

Cooler Heads

There are some engines out there that apparently run very cool, and it's not clear if that's because they are truly cool, or because of some artifacts in the CHT measurement process. Many of these engines are capable of producing very high power, and thereby very high internal cylinder pressures (ICP) at very low CHTs -- especially during cold ambient conditions!

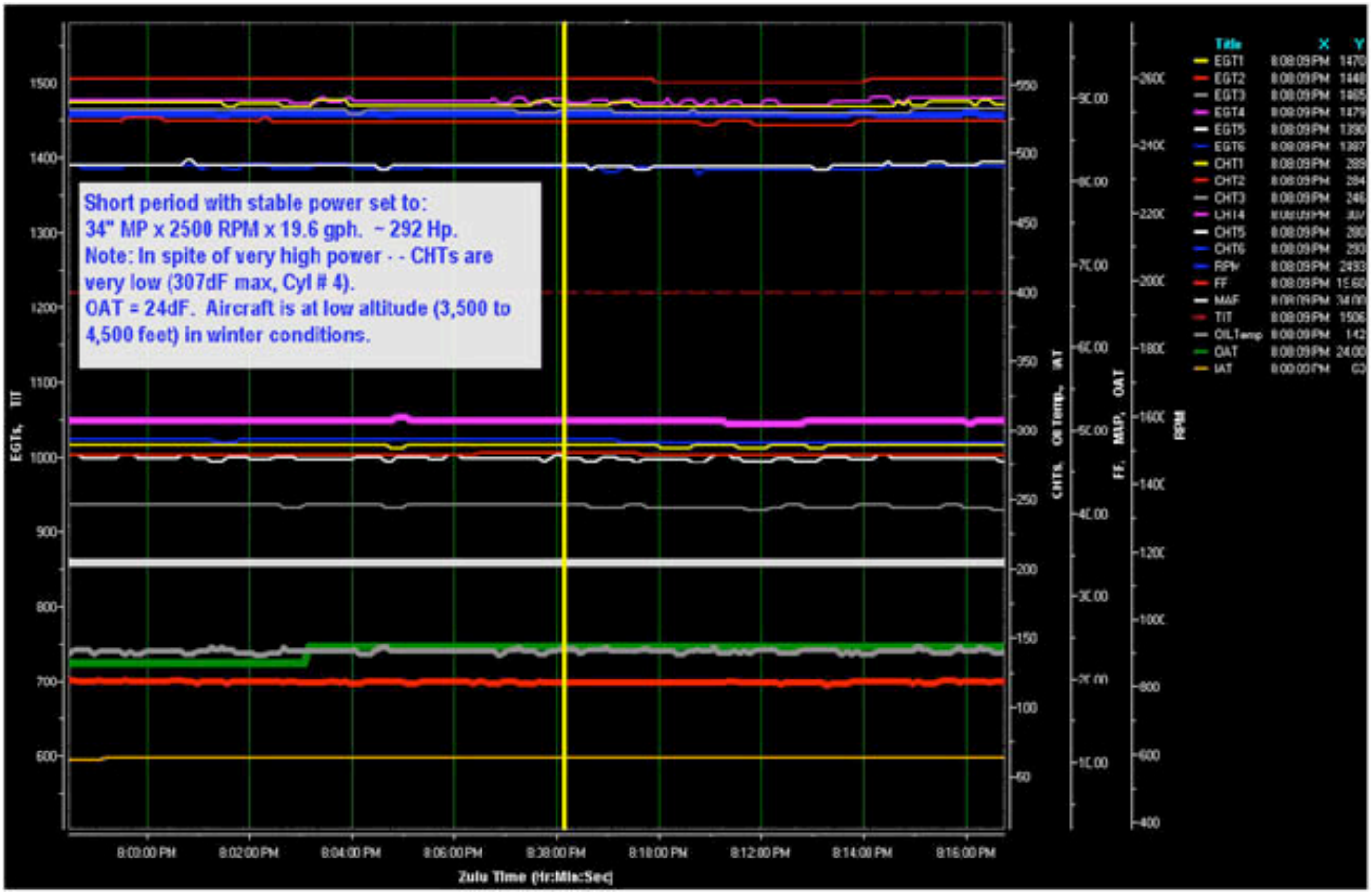
It just so happens that there are some engines that *can* use 380 °F as a "cruise CHT" and maintain ICPs within reasonable limits. However, even these engines shouldn't be operated at 380 °F in seriously cold air.

"Waitaminnit," you say. "Cooler is better, so how can this be true?"

Think it through. You take off from Florida with 70 °F weather, and you set up the mixture on a "large-displacement" engine at high MP and 380 °F on the hottest cylinder, with about 17.5 GPH fuel flow. For some engines (mine is one) this is an "aggressively good" high power setting and nicely lean-of-peak (LOP) EGT with reasonable internal cylinder pressures. We call it the "Go Fast Mode" at about 260 HP, which is about 84 to 87% of rated power on a 300- to 310-HP engine. (When an engine with a compression ratio of about 8.5 is flown LOP, fuel flow times about 14.9 equals HP. **Warning:** This calculation is good only when lean of peak!)

Now, you launch from Minneapolis, where it's -10 °F. You do the big mixture pull to your usual 17.5 GPH, and you notice, "Wow, the CHT is only 305 °F!" The colder air flowing over your engine is giving you more cooling, but the HP is still the same. For those who may have been taught "The Target 380 Method," the temptation is to increase fuel flow to bring the CHT up closer to the 380 °F target. You might end up with 21 or 22 GPH, nearly 330 HP, out of your 300 HP engine. You just became a test engineer. That is not a good idea. But it sure illustrates this is not a trivial issue.

Here's a graph of this condition:



Engine Monitor Plot -- winter, high-power condition. (Click here for larger version -- 207 KB.)

The vertical yellow line at about 08:08 is the EGView sliding marker that points to the data shown at the right side of the chart. The power is *very* high (about 94%), cylinder pressures are probably 800 to 900 PSI, and the airplane is bumping up into the yellow airspeed arc.

Why are the CHTs so very low? Well, first, we're a very low altitude, where the air is dense, and maximum cooling is available. Second, the airplane is haulin' ... er ... going very fast, also good for cooling. Finally, that cooling air is very cold.

I'm not so sure this is a good thing to do to our engines. We've become very comfortable with 85% when 80 to 100 °F LOP. We've run our own engines there a *lot*, hundreds or thousands of other pilots are running their engines there, many have gone to and beyond TBO, and we've got pressure data from the test stand that shows ICPs well within our "comfort range." We are not so sanguine about higher power settings. If you choose to do this, please report back in a few years!

The real point here is that any attempt to bring the CHT up to some mythical "target" will result in HP beyond 100%, and ICPs over 1,000! We know that's harmful; we've seen the test stand engines pop spark plugs right out at only slightly higher pressures!

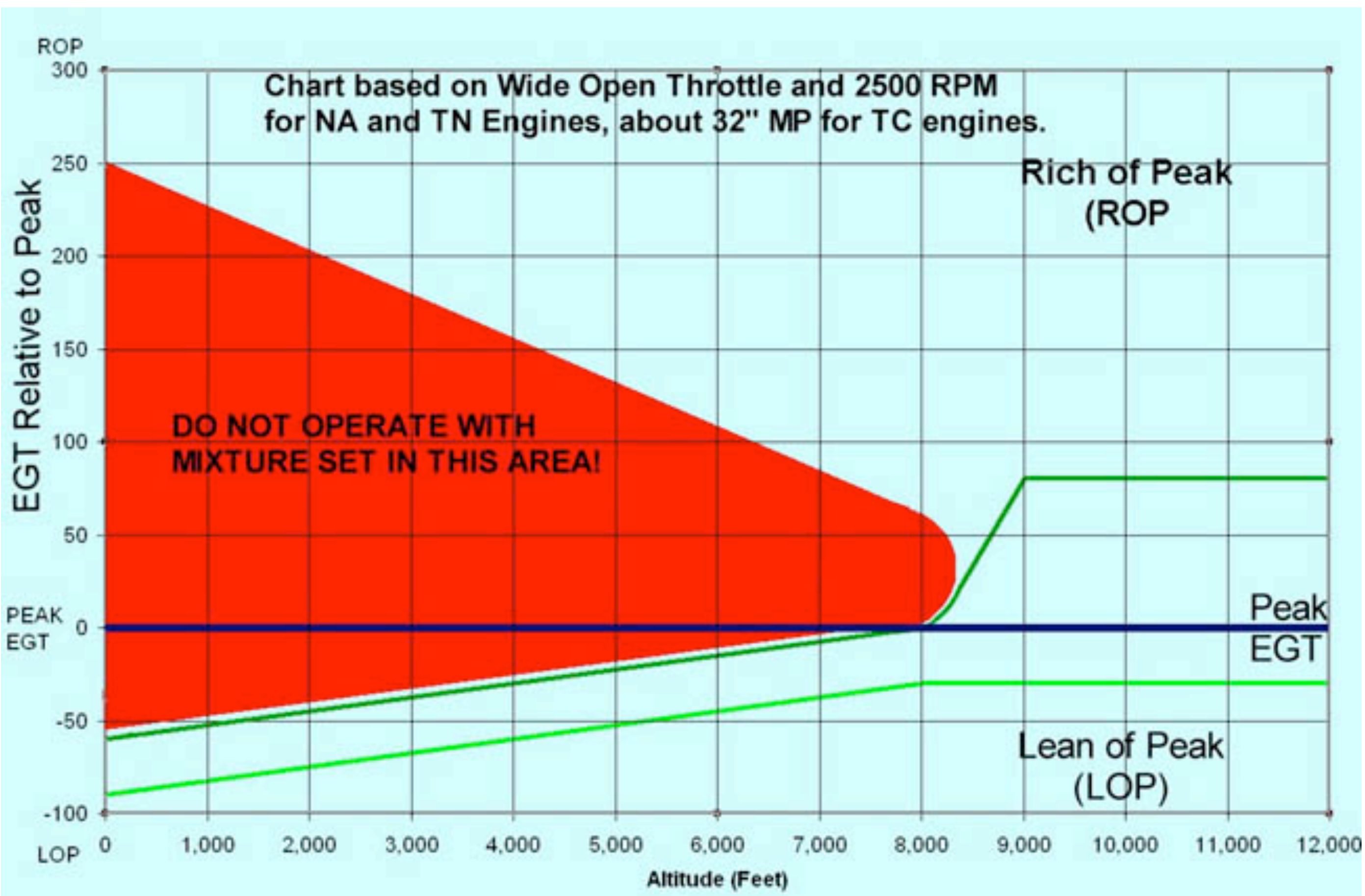
So what good are all these EGTs and CHTs, then? Just why did you get an engine monitor? Glad you asked. While some engines under some conditions may peak at 1400 °F EGT, and others at 1750 °F, and CHTs may peak at 280 to 450 °F (just grabbing numbers here), there is one number that will serve you well: the *difference from peak EGT*. No matter what inaccuracies there may be in the absolute value of the measurement, no matter what the conditions are, if you know peak EGT today, under these conditions "right now," then some incremental number of degrees from that peak EGT value will be a repeatable and reliably useful parameter for a large number of different engines under all conditions for routine operations.

What are these numbers? They're not quite as simple as a flat, fixed, "universal" number like 380 °F CHT, but they're quite usable. At and below 60% of rated power, no mixture setting will harm your engine, and 10 to 20 ºF LOP EGT is very close to the most efficient setting (best brake specific fuel consumption -- BSFC). The more power you set, the further from peak EGT you need to be. At 85% power, best BSFC is found across a broad range of LOP mixtures (think "flat curve," and see the charts in my last column with the big, red boxes), but keeping the EGT at 80 or 90 ºF LOP works really well to both keep the engine cool and to mitigate the peak internal cylinder pressures.

So, use 20 ºF LOP at low power (60%) and 90 ºF LOP at high power (85%).

Use a straight-line variation to connect those two points for all your LOP settings. If that mixture setting drives the CHT up near 380 °F, then lean a bit more. It usually doesn't take much. Leaning by an additional 0.5 GPH will normally drop the CHT's by 10 to 15 degrees after five minutes or so.

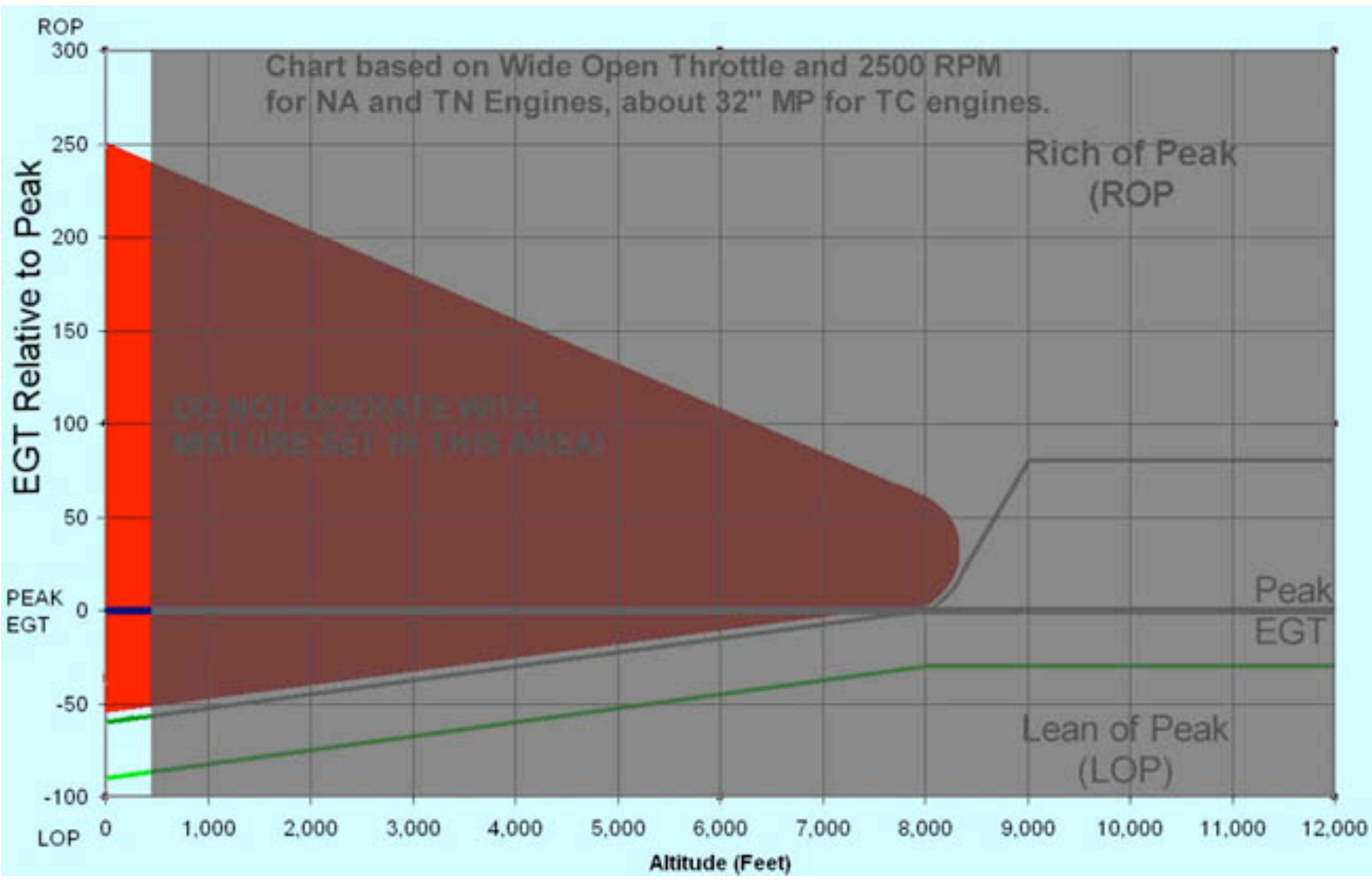
Here's a different view of those dangerous mixture settings that illustrates this:



Mixture Setting "Red Triangle." (Click here for larger version -- 105 KB.)

The lower (light green) line is where we'd suggest you should operate when LOP with the normally-aspirated engines (no turbo). The darker green line represents a more aggressive mixture setting that might be used when needed. Remember, all these lines and numbers are a bit "fuzzy!" We can argue all day over the precise placement of the lines, and the red triangle, and where the breakpoints are, but in the end, this is just an illustration of the general idea.

With a turbo-normalized engine, the engine thinks it's at sea level all the way to its critical altitude, so most of the chart goes away, like this:



Mixture Setting "Red Triangle" for Turbonormalized Engine.

The turbonormalized engine is so much easier to manage! Either run it full rich, or 90 ºF LOP (or a bit leaner if CHTs go above 380 °F).

The TSIO (and TIO) engines can attain much higher manifold pressures for takeoff and climb, but if the manifold pressure is limited to about 32" in cruise, the rules for the turbonormalized engines work pretty well.

How Much Power Is This, Anyway?

One common mistake is that people will check the POH and find the MP and RPM for a given percent of power, and then they'll lean from there to some LOP setting. That doesn't give you that same percent of power, it will be somewhat less. The chart in your POH is almost always drawn at "Best Power" (usually specified in very tiny print). As mentioned before, for *any* given MP and RPM (LOP only!), you can calculate horsepower by multiplying fuel flow in gallons times 14.9 for most normally-aspirated and turbonormalized engines, and 13.7 for most of the TSIO and TIO engines. There is some engine-specific variability on some of those engines, but you won't go seriously wrong with these numbers.

Remember, no one can specify any power setting with MP and RPM alone. All three parameters must be known and mixture is arguably the most important.

(For real engine-heads, the big variable is the compression ratio [CR]. 14.9 is based on the usual TCM normally-aspirated [and turbonormalized] engines at CR of 8.5 and 13.7 is the number for many of the TCM TSIO and the Lycoming TIO engines, with superchargers and CRs of about 7.5.)

On the other hand, if you are operating at high power and *rich* of peak (ROP, as in climb), you want the mixture set so that the EGT is 250 °F ROP (normally aspirated, sea level) or even as much as 350 °F ROP (for turbocharged engines). This will give you a bit more fuel flow than the charts and manuals call for, and that's good.

Once you've gone through the above drill a few times in a specific airplane, you will have a pretty good idea of the fuel flow that works. This is another number upon which you can hang your hat. On my engine -- a TCM IO-550 with Millennium cylinders and the Tornado Alley Turbonormalizer -- 17.5 GPH is my magic number. That's very close to 260 HP, a good, aggressive, "go fast mode" power setting. I've got about 600 hours on that engine now, all of it at that power setting. Compressions are fine, borescope looks great, and the engine is running smoothly and well. There have been *no* issues, no cylinder work.

What percent power is that, anyway? Ah, now we get another "slippery number." Nominal HP on this engine is 300, so that would be about 87%. But we know the Millennium cylinders move air just a bit better than the factory cylinders, so full power is probably 310, or 315, so that number could be 84%, or 83%, depending on which "max. HP" you use in the calculation.

In summary, 380 °F is a useful number to keep in mind for metallurgical purposes. It may not be a good number upon which to fixate for a cruise mixture setting for the long term.

Be careful up there!

More from AVweb's Pelican is available [here](#).