Lean for Cruise

Setting the mixture control for cruising flight shouldn't be complicated. Yet it's persistently one of the most contentious topics of engine management. That's probably because the gritty details of gasoline engines are complicated.

The good news is you can decide how deep a dive you want to make. The more theory you're willing to embrace, the more efficiently you can operate and the more money you might save. But there's nothing wrong with just keeping it simple and getting on with the rest of your flight. As always, POH guidance is the authority, but if it's lacking or you want to supplement that guidance, read on.

Utter Simplicity: Don't Bother

If you're making a short flight at lower altitudes in a low-power engine—as most training flights are—you can get away with never touching the mixture knob. You'll burn more fuel than you need, and the oil will be dirtier than it might have been at your next oil change (page 98). You might need to clean your spark plugs more often (page 94). However, these aren't the end of the world. Just to be clear, there are two big caveats here. This assumes you'll use a moderate to high power setting. Extended low power with a full rich mixture can lead to lead deposits on the valves. Also, this is only low altitude. At higher density altitudes you must lean for takeoff (page 36) and lean for climb (page 40).

TIP

There's no rush to set a mixture for cruise. Level off and let the airspeed stabilize before using whatever method you prefer to lean for cruise flight.

"Do No Harm" Leaning

If you're cruising at higher altitudes or you just want to save a little gas, you'll have to do some leaning just to maintain engine power. However, you can still keep it simple.

If pilots fear aggressive leaning it's because they fear engine damage. That's a legitimate fear. Engine damage is expensive at best, and potentially lethal if

WHAT'S WRONG WITH 50°F RICH OF PEAK EGT LIKE MY POH SAYS?

The short answer is "nothing ... maybe."

It's "maybe" because there are too many different engine/prop/airframe combinations and situations to say for sure. But one thing is for sure: Some of those combinations will suffer if you spend many hours at 75 percent power and 50°F ROP EGT. Will yours? Again ... maybe.

As we lean, the engine produces more power even though there's less fuel because we're generating more heat and pressure as that fuel burns more efficiently. More heat = higher EGT. The engine reaches maximum power just before EGT peaks, and produces maximum efficiency sometime after. Power drops off rapidly as the mixture is further leaned because heat and pressure (and EGT) fall again.

LEANING USING EXHAUST GAS TEMPERATURE (EGT)

EXHAUST GAS TEMPERATURE (EGT)

MIXTURE DESCRIPTION	EXHAUST GAS TEMPERATURE (EGT)
RECOMMENDED LEAN (Pilot's Operating Handbook)	50°F Rich of Peak EGT
BEST ECONOMY	Peak EGT
BEST POWER	150°F Rich of Peak EGT

This is why many POHs (particularly older ones) recommend leaning to 50°F-150°F ROP EGT for best power and peak EGT for best economy.

Unfortunately, this one-size-fits-all solution ignores how different engines have wider or narrower danger zones. (See "Can You Run an Engine Too Hard in Cruise?" on page 43.)

This system typically relies on a single EGT sensor that aggregates the EGTs from several cylinders. This means one of your cylinders could be in the danger zone if you have significantly uneven fuel distribution—and you'd never know. Well, until it needed premature overhaul.

But then again, if running 50°F ROP saves you 1.5 GPH versus a safer 100°F or even safer 150°F, and that saved you $7000, the money could pay for a couple cylinder replacements. Maybe that's not bad math.

it means engine failure in flight. Indiscriminate use of the mixture control could destroy an engine.

So the most important criteria is “do no harm.” This means digging in your POH a bit to find what RPM (and MP with a constant-speed prop) setting produces 65 percent power for your cruise altitude. At 65 percent power, it’s *almost* impossible to damage an engine with leaning, so adjust RPM (and MP) for that power. If you want even more security, estimate 60 percent power where the mixture setting can’t do any harm at all no matter how aggressively you lean.

If the POH publishes a fuel flow for that power setting (including altitude and temperature) and you have a fuel flow gauge, you can lean to that fuel flow and call it good, so long as the engine runs smoothly.

Without a fuel flow gauge, or just to get the mixture more dialed in, lean until the engine begins to run rough, and then enrichen until it’s running smoothly again. That’s it. You are close to the peak pressures that engine can produce at this power setting, but because you’re at 65 percent power or less, it’s not a problem. (See “How Power, Pressure, and Temperatures Change with Mixture” on page 48.)

If you don’t have a turbocharger, cruising at the altitude where WOT gives you 65 percent power will get you the highest true airspeed for this fuel burn. If that works with winds for a decent groundspeed, you’re golden.

If you want to fly faster—and who doesn’t?—you’ll need more than 65-percent power. You can simply use the fuel flow in your POH if you have a fuel flow gauge. However, you should know manufacturer fuel flows may provide little or no margin against engine damage at higher power. Simple solution: Consider using 10 percent more fuel flow than published at greater than 65 percent power. If you have a single-probe EGT, you can use it. However, read “What’s Wrong With 50°F Rich of Peak EGT Like My POH Says?” on page 46 before you do.

Without a fuel flow gauge or EGT of any kind, you’ll have to estimate. Lean until engine roughness. Do this such that it takes no more than 10 seconds to reach this rough point. The mixture is passing through a potential danger zone as you lean.

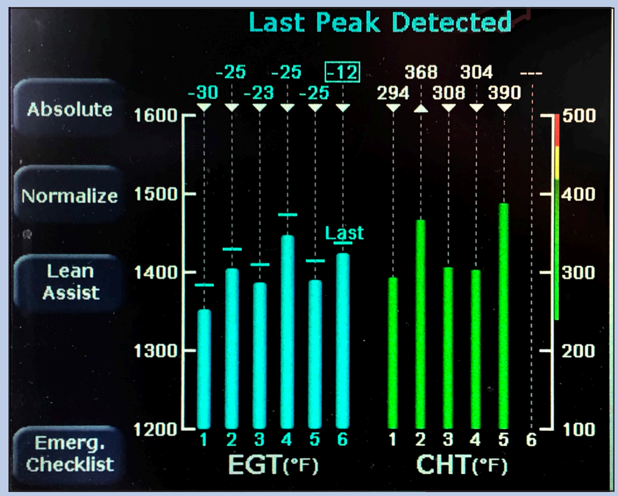
Note the position of the mixture control. Now *re-enrichen* to a position halfway between this rough-running setting and full rich, or the point where engine RPM or MP starts to decrease, whichever happens first. That’s more fuel than you need to burn, but it should be safely on the rich side.

(To understand why there’s a potential danger zone, see “How Power, Pressure, and Temperatures Change with Mixture” on page 48.)

USING LEAN ASSIST

Many multi-probe engine monitors have a function to help you lean for cruise. Each one is a bit different, but a common theme is that the monitor watches all the EGTs rise and flags the one that starts falling first. Most only work reliably when leaning for ROP, but some work well running ROP or LOP. Other features might be changing the scale of the readout so it’s easier to see each EGT rise and fall (common on older “orange bar” monitors) or even step-by-step instructions for leaning.

Remember that many of these systems use a fixed number of degrees ROP or LOP as a target, rather than an adaptive number based on power. It’s your right to lean cooler than the monitor’s software recommends, lean or rich of peak.

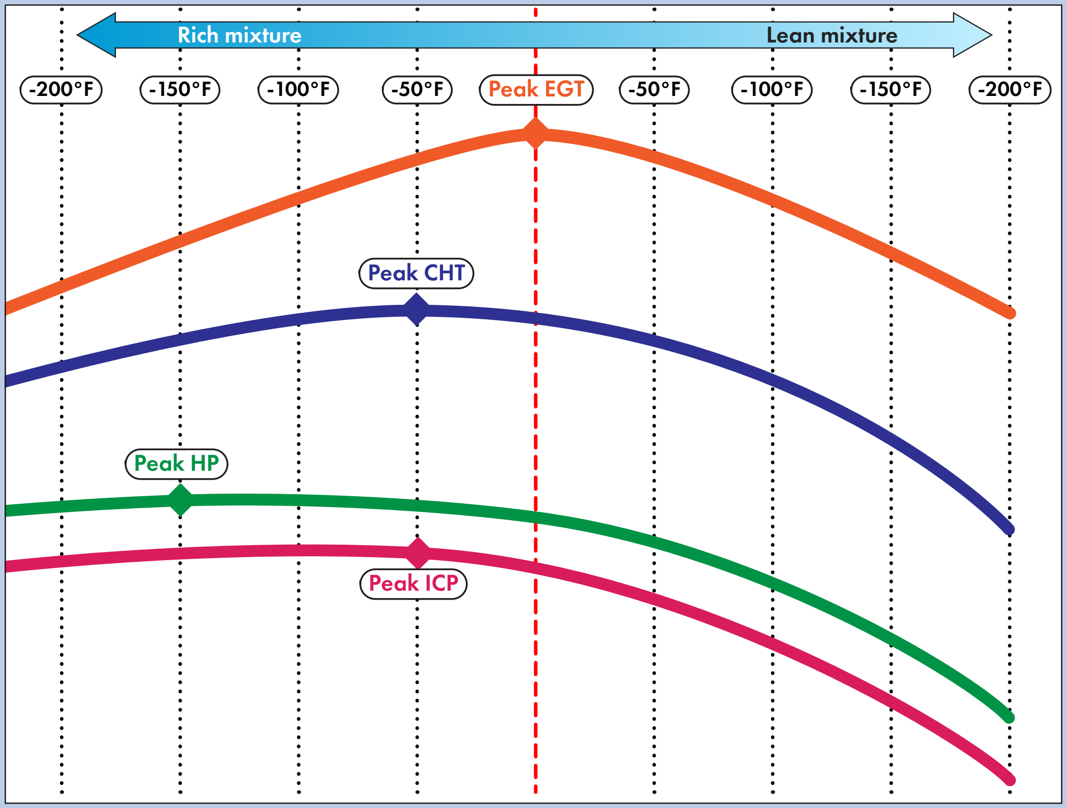


Some also show percent power, but that’s usually based on an ROP calculation and is incorrect if running LOP. You can calculate LOP power if you know the fuel flow. LOP power is 15 times fuel flow in GPH. So if you’re showing 9.2 GPH LOP, that’s 15 * 9.2 = 138 HP. If you’re engine is rated for 200 HP, that’s 138/200 = 69% power if running LOP.

“Do No Harm” Leaning 2.0

If we could, we’d have sensors to measure the pressure inside our cylinders, the onset of explosive detonation, and the amount of oxygen consumed by com-

HOW POWER, PRESSURE, AND TEMPERATURES CHANGE WITH MIXTURE



To better understand how this all works, imagine a one-cylinder airplane engine happily running in flight. Both air and fuel are entering the engine, mixing, and getting ignited by the spark plugs. This combustion means the fuel combines with oxygen in the air to generate a lot of heat. That heat causes the rest of the air (mostly nitrogen) to expand rapidly. The pressure inside that cylinder skyrockets and shoves the piston down, which spins the prop and away we fly.

You'd think in a perfect world we'd have exactly the right ratio to burn all our fuel with just enough oxygen. That would be the perfect mixture.

That never happens. Even if we managed to get a ratio of exactly 14.7:1 of air to fuel (the perfect ratio for gasoline engines), we'd never burn all the fuel because there would still be areas within the cylinder that had a little too much fuel or a little too much air. Life is like that.

If we want maximum power, we want a little extra fuel so that every place there's enough oxygen available we burn at least some fuel. There will always be lots of oxygen coming out the exhaust, but for the sake of discussion, you could say we run out of air before we run out of fuel.

If we want maximum efficiency, we want just enough fuel to squeeze heat out of every drop we can. We won't have as much total heat generated inside the engine as we would with excess fuel, so we don't have as much total power. However, we get the most out of the fuel we do put in. For simplicity: We run out of fuel before we run out of air.

Back to our one-cylinder engine cruising in flight several thousand feet in the air: You haven't leaned since takeoff because you didn't lean for climb (page 40). It's now way rich, so rich that it's far below maximum power. It's running out of air during combustion long before it runs out of fuel. The extra fuel interferes with combustion and there's not much heat to pressurize the cylinder and turn the prop.

You begin to lean for cruise flight. Even though less total fuel gets into the engine, more fuel gets burned during combustion than before because it can "find" some air. The pressure in the cylinder increases. We call this the intra-cylinder pressure (ICP). That means more heat, which is more power, so horsepower increases. Our engine puts out more power and we fly faster on less fuel than before.

As you keep leaning, horsepower begins to level off as the ICP begins to level (HP actually levels off first, but again: simplicity). Then HP and ICP reach maximums in quick succession right about the "perfect" mixture. We're generating lots of power and flying fast, but boy is our engine hot.

As you lean further, HP and ICP fall rapidly because even though we're burning all the fuel, there's just less of it so engine temperature and power decrease. Our airspeed decreases again, but now we're flying that speed burning far less fuel.

If you keep leaning, you'll get so lean that the extra air interferes with the flame reaching all the potential fuel. The engine misfires—and you push the red knob back in some to keep this engine flying.

Here's the catch: As you leaned, you passed through a zone between a safe maximum power and a safe maximum efficiency where the pressures and temperatures inside the cylinder could have damaged the engine.

So your job when leaning is targeting a "safe best power" somewhere well ROP EGT or "safe best efficiency"somewhere LOP EGT. You should stay on one side or the other of that potential danger zone.

Unfortunately, ICP sensors are too expensive for flight and the oxygen sensors cars use aren't approved in certified airplanes. However, CHT and EGT on our engine monitor are a decent proxy. CHT rising and falling with ICP makes sense: The higher the ICP the hotter that cylinder will get. It's not a perfect match, but we'll leave that discussion for the engineers.

EGT rising with increasing combustion also makes sense as the gasses inside the cylinder are getting hotter. EGT actually peaks after ICP, HP, and CHT all begin to fall. Again, the reason isn't important for actually using this relationship. Eventually EGT drops as there's just less heat being generated inside the cylinder.

Starting from a situation that's way over-rich, EGT and CHT rise basically in step with ICP and HP. HP begins to level off somewhere around 150°F rich of where EGT will peak. About 50°F ROP, ICP and CHT reach their highest point. HP is pretty flat here. Continuing to lean makes CHT, ICP, and HP all fall as EGT peaks. Lean further and EGT falls. Note that the absolute value of EGT is irrelevant here. It's only relative to where the peak is.

This is why many POHs recommend 50°F-100°F ROP EGT for best power. The highest ICP/HP is in that zone. It's also the zone most likely to damage your engine at higher power settings, but the manufacturer doesn't have to pay for that.

Many POHs use peak EGT for best economy. You can also see why now: That's just about where HP begins to fall off steeply, so you burn a bit less fuel without a big decrease in power. That looks good in the airplane performance numbers—and still sits in the zone that could damage your engine under the wrong conditions.

bustion. We'd have computers to control everything. Every late-model car has some of these. In the cockpit, all we have is a red knob, our brains, and EGTs.

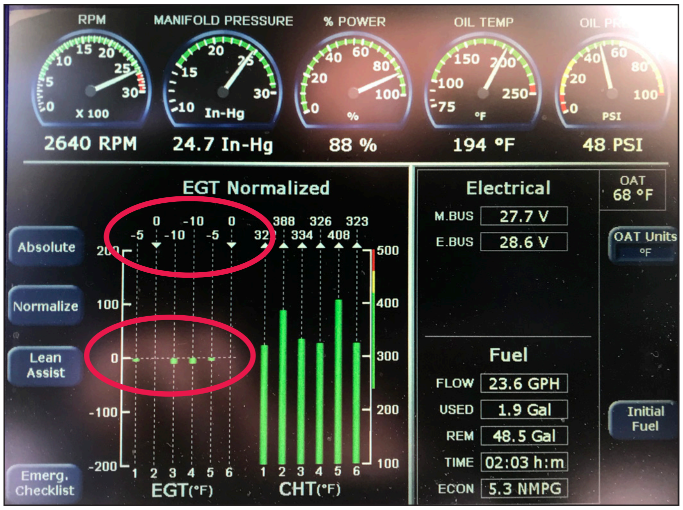
EGT is a proxy for the pressure and oxygen sensors we wish we had. (Again, see "How Power, Pressure, and Temperatures Change with Mixture" on page 48 for details.) With EGT displays for each cylinder, we can dial in the fuel flow to ensure all cylinders are in a safe zone.

Here's the catch: The higher your power setting, the further ROP or LOP EGT you must be to stay safe. Furthermore, not all engines are equal. Some engines are derated to produce less peak power than they theoretically could. Others squeeze all they can for their size. The higher the engine's rated power for its size, the further rich or lean of peak you must be to be safe. (See "Can You Run an Engine Too Hard in Cruise?" on page 43.)

The spread between safe ROP and safe LOP can be quite wide. Here are numbers that are safe for just about any airplane engine, derived from lab testing by the folks at GAMI and promoted through their Advanced Pilot Seminars.

Power	Minimum°F rich of the richest cylinder	Minimum°F lean of the leanest cylinder
85%	220°F	75°F
80%	200°F	60°F
75%	180°F	40°F
70%	125°F	25°F
65%	100°F	0°F

So if you set your cruise power (page 42) for 75 percent, you could safely lean for an EGT 180°F ROP EGT or richer, or you could lean for an EGT 40°F LOP EGT or leaner. *But you should limit operation anywhere between those two settings to no more than a minute, and less is better.* (See "How Wide is the Danger Zone?" on page 51 for a different way to visualize this.)



Zero your EGTs with normalize mode once you're done leaning for cruise. Unless you change power settings, you can simply lean or enrichen as needed if the EGTs drift up or down.

You might look at those numbers and say, "I couldn't get my engine to run 200°F ROP even if I ran it full rich!" That may be true. Consider three things.

Your engine may be derated, so what you call 85 percent power would be only 70 percent power in another airplane. Another factor may be that you use a single EGT. This doesn't let you see where the richest or leanest cylinder actually peaks because all the peaks are smeared together. Finally, this is "do no harm." It's not that running 100°F ROP at 80 percent power *will* cause damage; it's that 200°F ROP absolutely *won't* cause damage. And it's progressive. If 200°F ROP is absolutely safe, then 100°F ROP is less assured. But 100°F ROP is more margin than 50°F.

There's one other key takeaway from this chart. Both 180°F ROP and 40°F LOP are 75 percent power. Both yield the same airspeed and similar cylinder temps. However, the lean one burns less fuel and puts less carbon in the oil and on the spark plugs.

If you can run LOP, you can save a lot of gas. Unfortunately, not everyone can run smoothly LOP.

Checking If LOP is an Option

To safely operate LOP you need a fairly even fuel distribution. In a perfect world, all cylinders in the engine would have exactly the same amount of fuel and air. As you leaned, the power output and EGT for each cylinder would be identical as they rose and fell together. That never happens.

> **TIP**
>
> Some engines with a constant-speed prop won't run LOP at higher RPM, but can at lower RPM.

Instead, each cylinder gets a slightly different amount of fuel and air and produces slightly different power. So a four-cylinder engine producing 200 HP might get 48 HP from one cylinder, 47 from another, 53 from the third, and 52 from the last one. The greater the differences between cylinders, the rougher that engine will run.

As you lean, all cylinders get leaner, but they will each pass through the peak EGT at different points. Because power drops off faster on the lean side of peak, the power differences between cylinders are greater when running LOP. If the differences are too great, the engine will be unacceptably rough.

Fuel distribution, a.k.a. GAMI spread, is something you can test in flight (page 58). In general, unless the difference in fuel consumption between your richest cylinder and your leanest is less than 0.5 GPH, you can't run LOP. The more cylinders you have, the more likely this will be a problem. This is why you must have a multi-probe EGT and CHT engine monitor to conduct the operations outlined below. You must have visibility into what's happening for each individual cylinder.

Generally speaking, Continental fuel-injected engines can run LOP with little or no problem, while Lycoming fuel-injected engines may have trouble without modifications (page 119). Some carbureted four-cylinder engines can run LOP, although judicious use of carb heat might be needed (page 65). Virtually no horizontally opposed six-cylinder carbureted engine can run smoothly LOP. (Radial engines are their own story.)

Leaning ROP Using Multi-Probe EGT

If your engine can't run LOP, then you simply set cruise power and check the POH (or your MFD) for your current percent power. Check how far ROP you should run in order to stay out of the danger zone, with accommodations for your comfort level and specific engine installation. As you lean, EGTs will rise. Watch your EGTs looking for *the first one to reach peak*. Use lean assist (page 47) if you have it.

Whichever cylinder is running leanest will reach peak EGT before the others. (In a perfect world with perfect instruments, it would always be the same one, but as we've said, life isn't perfect.) If you have lean assist, this value will probably flash. Note the EGT reading and enrichen until that cylinder's EGT has lowered by the minimum amount you've chosen for your power setting. You're done.

Leaning LOP Using Multi-Probe EGT

If your engine can run LOP, the process is similar. Start by choosing a target power you want and determining how many degrees LOP you need. Next, lean the mixture fairly rapidly until the engine begins to run rough, and then enrichen only enough so you're not worried it will actually quit. Some people refer to this as "the big pull." You should be well LOP at this point, but not generating enough power for comfortable cruise.

Now reference EGT as you slowly enrichen. EGTs will rise, but this time it's because you're approaching peak EGT from the lean side. (If they fall, your engine ran rough before reaching LOP and you have no choice but to run ROP.) Most lean assist functions get confused by this, so you might do better without using it. Just watch the EGT absolute values.

Like before, as you enrichen you're looking for the first cylinder to reach peak—but this time that's the richest of your cylinders. Note the peak value, and then *lean* to bring that EGT back down by the target number of degrees for your power setting. Unlike ROP, the LOP numbers in the chart here are pretty good for any engine because the range isn't that wide. Again, you're done.

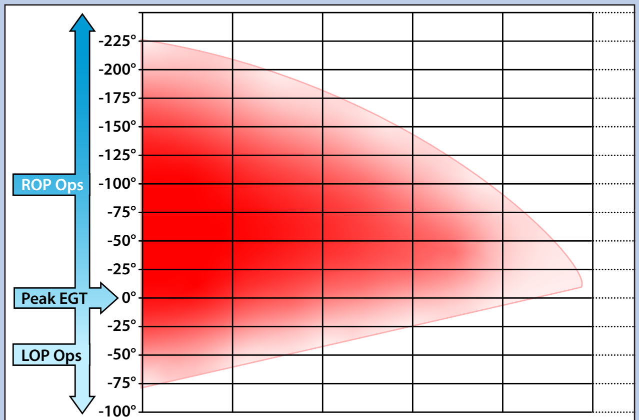
Maintaining Mixture as you Cruise

Once you have a working mixture setting, note the EGT of the cylinder you used to set your mixture so you can maintain it as you fly through variations in temperature and pressure. Even better is engaging a normalize mode on your engine monitor and adjusting the mixture to maintain a normalized value of zero. Just remember that if you're running ROP, you'll enrichen to reduce EGT, but if you're running LOP you'll lean to reduce EGTs.

You can keep using your current mixture setting with altitude changes so long as you maintain your current power setting. If you change altitude, adjust RPM and/or MP to maintain the same power and tweak the mixture to maintain the same (or normal-

HOW WIDE IS THE DANGER ZONE?

The chart on page 49 shows that the dangerous range for mixture setting diminishes with percent rated power. By 60 percent power, it's essentially nonexistent. This is a bit easier to visualize as a chart Gordan Feingold dubbed "The Red Fin." The percentage assumes a high-output engine. If your engine is derated, your "red fin" is smaller.



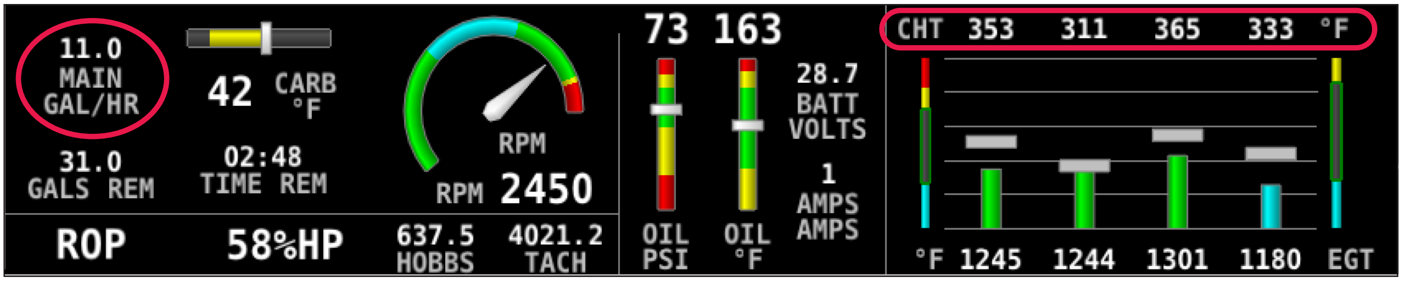
Power	85%	80%	75%	70%	65%	60%
LOP–200 hp	11.4 GPH	10.8 GPH	10.1 GPH	9.4 GPH	8.8 GPH	8.1 GPH
LOP–300 hp	17.0 GPH	16.0 GPH	15.0 GPH	14.0 GPH	13.0 GPH	12.0 GPH

When running LOP, fuel flow determines horsepower, so a great addition to a red fin chart is calculating the fuel flow you'd expect LOP for different percent power.

First calculate your horsepower for the major percentages shown on the chart. For a 300-HP engine, 70 percent power is 300*0.7 = 210 HP. A 200-HP engine would be 200*0.7 = 140 HP.

Divide the HP for each power setting by 15 to get the expected fuel flow and write that on the chart. This is your LOP fuel flow at each power setting. It would be 14 GPH for the 300-HP engine, but only 9.3 GPH for the 200-HP engine.

You can use this in two ways when running LOP. After you've leaned using whichever method you want, verify that the delta between the peak EGT and current EGT on your richest cylinder was large enough for your current fuel flow to stay out of the danger zone. Or you can go from ROP directly to the fuel flow for the power setting you want and do a quick check right then that peak EGT is sufficiently far away. Over time, you'll learn the fuel flows that are reliably safe for your engine and lean directly for those simply verifying smooth operations and acceptable, even CHTs.



Experience lets you lean for fuel flow you know is about right and watch the CHTs for individual cylinders. Adjust for the specific conditions of the day.

ized) EGT. If you can't maintain the same power, you can repeat the leaning process. You may want to repeat it with a major change in environment, such as going from IMC to VMC or vice versa, or crossing a strong temperature gradient.

Lean By Fuel Flow

Keep a log of the fuel flow you use for different power settings over many flights. For your engine, a given power setting should always have a specific fuel flow for running ROP and another for LOP. These usually vary with altitude by only 0.1-0.2 GPH even over several thousand feet. If you use a wide range of altitudes, build a chart with your common choices.

Over time, you'll know the fuel flows for your airplane at different configurations. Eventually, you can lean for cruise by simply setting a fuel flow you know works for the power setting you have. Still, it's a good habit to run through a full leaning exercise once in a while to ensure nothing has changed. A type club for your plane may have published ROP and LOP fuel flows for different power settings for your engine. That's a great reality check that you're doing things correctly. Just remember that each engine installation is a bit different. Your mileage will literally vary.

Run LOP Using CHT

An alternate method promoted by engine guru Mike Busch for LOP operations is to lean for condition and a maximum CHT. It's worth seeking out his exact guidance if you want to try it, but in a nutshell he'll do a "big pull" to get safely LOP. Then if he wants maximum efficiency, he'll stay well LOP so long as he has acceptable speed and smooth engine ops. If he wants to go faster, he'll enrichen as much as practical while keeping his hottest cylinder at roughly 380°F.

He's using absolute CHT instead of relative EGT to stay out of the danger zone, but the goal is the same.

Turbocharging and Other Caveats

There's no leaning for climb with turbocharged engines, other than some that need an initial leaning after takeoff. There usually is leaning for cruise, but it's often to a specific fuel flow for the power setting.

Turbocharged engines also have a gauge for turbine inlet temperature (TIT). TIT is essentially an EGT reading, but measured at the inlet to the turbocharger. Unlike EGT where absolute numbers rarely matter, there will be a TIT limit that must be respected. It's commonly 1650°F-1700°F. That's because stainless steel parts begin to soften and "creep" somewhere north of 1600°F. Even though TIT is essentially exhaust gas, it's often hotter than individual EGTs because the gas is compressing as it's forced into the turbine. Keep an eye on TIT whenever leaning a turbocharged engine and respect the published limits.

Along those lines, EGTs routinely above 1600°F during normal flight are worth bringing up with your mechanic. Even a stainless steel exhaust system could fatigue if it gets too hot for too long.

Can't Someone Just Tell Me What to Do?

There simply is no single way to lean for cruise that works well for every situation and engine. Hopefully, this discussion gives you a kind of flow chart.

For low, short flights at high-to-moderate power at least lean for climb (page 40). This will net more power and less wasted fuel even if that's all you do. To simplify and be safe, use 65 percent power or less when efficiency matters and you can lean by any method of your choosing with little worry.

For higher power, err on the side of burning extra fuel now if you don't want to risk a top overhaul later. Or, if you have the desire, instrumentation, and mental bandwidth, you can run at higher power settings and mixtures LOP (or not excessively ROP). The rewards can be well worth it.