Manifold Pressure Sucks!

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If you fly behind a piston engine with a controllable-pitch propeller, the manifold pressure gauge plays an important part in the power settings you use. Few pilots, however, have any real understanding of what the instrument actually measures or what its readings truly signify. Pelican to the rescue! Read this column by AVweb's John Deakin and you'll be able to teach your CFI and A&P a thing or three about MP.

The manifold pressure (MP) gauge is a very simple instrument, but what it does is a mystery to many pilots. Simply put, if you do not fully understand what that instrument is telling you, you cannot possibly understand the engine, engine management, power settings, or troubleshooting.

Quiz Time

First, allow me to pose a few rhetorical questions to help you understand why there's more to this subject than meets the eye. You might be uncomfortable with the thought of actually doing some of these things to your engine -- and that's fine -- but I ask that you visualize them as a mind exercise and think about them, please.

This entire column will deal only with normally-aspirated engines -- those without superchargers or turbochargers. I'll be dealing with the fire-breathers in another column.

Question: Assume that someone -- perhaps a CFI quoting a poorly-done old POH, or perhaps just regurgitating what his CFI taught him -- has told you that the first power reduction after takeoff should be to 25 inches and 2,500 RPM. Leaving aside the issue of whether this is really a good procedure, let's assume you take off and dutifully pull the throttle back from about 29 inches, to exactly 25 inches. Then you pull the prop control back from 2,700 to 2,500. Are you surprised to see the MP rise to 26 inches or so as the RPM comes down? Do you understand clearly why that slight rise occurs?

Question: Suppose you leave the throttle wide open after takeoff, and just reduce the RPM from 2,700 to 2,500 (usually a better choice in the big-bore flat sixes). What would you expect to see the MP do, and why?

Question: Suppose you do a full-power runup in position before releasing the brakes (another bad procedure, but never mind). You note the MP and release the brakes. What will the MP do during that takeoff roll and the early climb, and why?

Question: Do you know (in general) where the "sensor" is for the MP instrument, and how it works? Which would you think is more stressful to the engine's intake manifold plumbing: a power setting of 12" MP (in a power off descent, for example), or 30" at takeoff power? Why? How is that pressure transmitted to the instrument you're reading?

Question: Your airplane is sitting at rest, engine not running, at a sea-level airport. What should the MP show? Suppose you're parked at an airport at 5,000 feet above sea level; what MP indication would you expect? What else can affect that reading? Suppose you know what it is supposed to show, but its two inches low in an airplane you've never flown before? What effect would that have on your flight? Would you depart with it showing that error? Could you correct for it? How?

Question: Suppose you start the engine and idle at 1,000 RPM to warm the engine. What will the MP show at sea level, or at that 5,000-foot elevation? Suppose you just happen to know the answers to these two questions in your own airplane, and one fine day you notice the MP is three inches higher than normal at 1,000 RPM while warming up? What would you think? Suppose the MP was lower than normal; can you think of a possible cause for that?

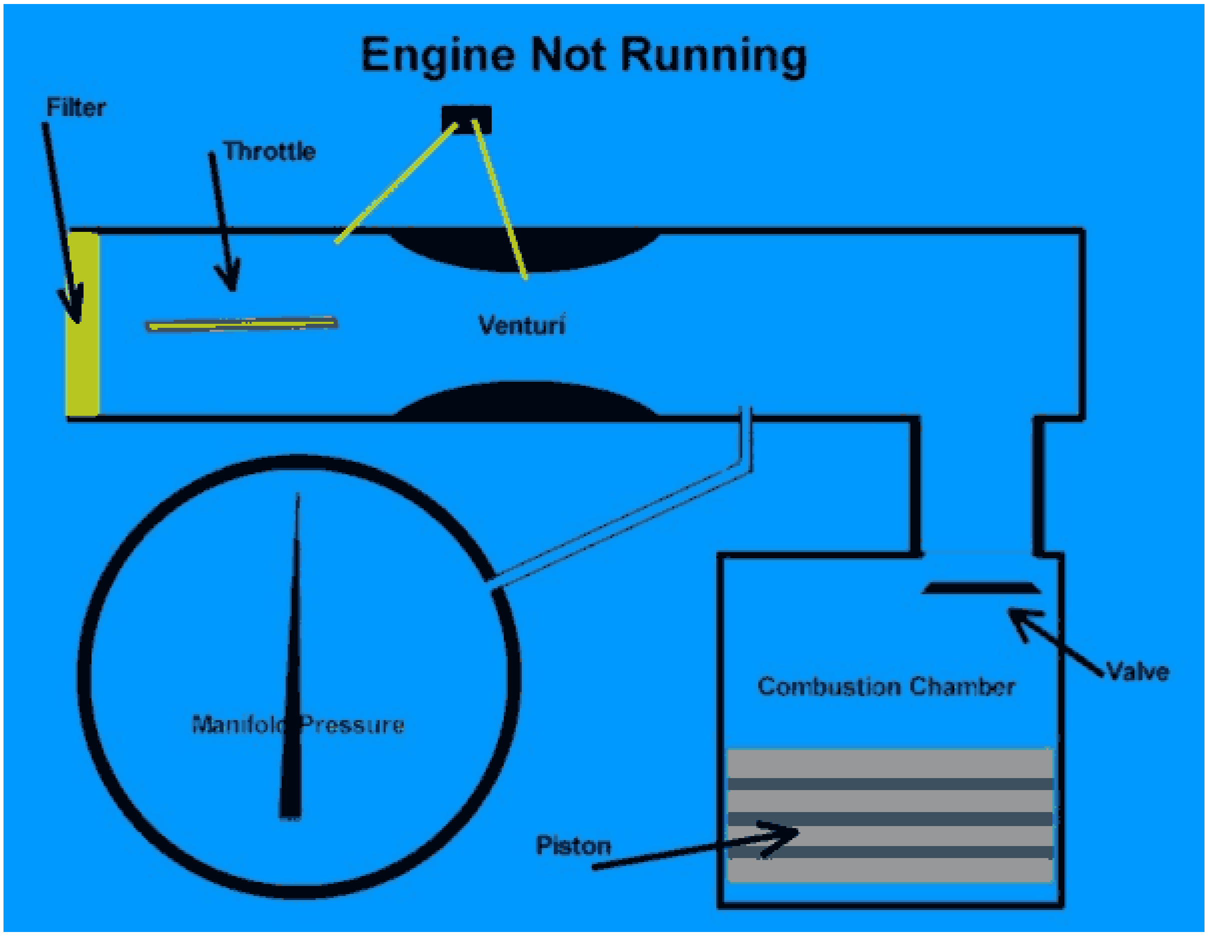
Question: Suppose you're cruising at 10,000 feet, full throttle, 2,500 RPM, and you cycle the prop between 2,700 (redline), and the lowest it will go, perhaps 1,200 RPM. What would you expect to see the MP do during this huge variation in RPM?

Question: Finally, suppose you're sitting in the runup area, ready to go, and you notice an audible whistle coming from the engine. What would you suspect, and what would you do about it?

Suction, Not Pressure

First, let's get rid of this idea of "pressure," because what the MP instrument of any normally-aspirated engine really shows is lack of pressure. In short, with the engine running, the MP gauge is always reading suction -- it's just marked with numbers that don't make that obvious.

Let's look at a normally-aspirated engine at rest, using the graphic below.



I have deliberately made this a very primitive schematic, something I call a "concept schematic" in my ground school classes. I've left out everything that is not essential to this discussion, and have drawn a very simple one-cylinder generic induction system. In real engines, of course, there are multiple cylinders, curving ducts, many more parts, carburetor heat or alternate air, etc.

Not Started, Yet

The ambient air has equalized in all parts of the engine portrayed here, represented by dark blue. I've shown the throttle (yellow) fully open here, but with the engine at rest it doesn't matter -- even with the throttle fully closed, there's enough of an opening for air to get by and equalize. (The throttle never really closes all the way -- a "fully-closed" throttle must still pass enough air for the engine to idle.) In this picture, the air pressure is at ambient pressure in the intake, in the induction plumbing, and in the combustion chamber. This will show on the MP gauge as 29.92 inches at sea level on a standard day. I know, it's hard to read it that accurately on the usual instruments, but you should see it very close to 29.9, and that's "close enough." If the sea-level airport has a big high-pressure area located over it with a local station pressure of 31.10, for example, then your gauge should show 31.1 inches of manifold pressure. If the airport is located at some higher elevation, the MP gauge will show an inch less for each thousand feet above sea level. (This rule-of-thumb is close enough at normal airport elevations, though it breaks down at altitudes above 10,000 feet.)

It is a good habit to note the MP gauge reading before engine start, and do a quick calculation to see how close it is. Set your altimeter to the field elevation, note the altimeter setting in the Kollsman window, subtract one inch per thousand feet above sea level, and your MP gauge should show very close to that value with the engine not running. At a 6,000-foot elevation airport, for example, set 6,000 on the altimeter, read (say) 29.5 in the Kollsman window, subtract six, and check that your MP gauge shows approximately 23.5 before start.

Anything else <u>is an error in the instrument.</u>

At that 6,000-foot airport, suppose it actually reads 22.5 (one inch too low), after you double-check your procedure. That would indicate that for any power setting you want, you should set the MP one inch low to correct for that error.

Take that "Static Manifold Pressure" reading, subtract about one inch (for most engines), and you get the reading you should expect to see at full throttle on takeoff. (We'll get to the reason for the one inch soon.) If you don't see that much MP on the takeoff roll, something is seriously wrong. You should probably abort and investigate.

Digressing briefly, how does the engine figure out how much fuel to pass into the induction system? Good question! There are several variations on this, the oldest being the venturi, and differential pressure.

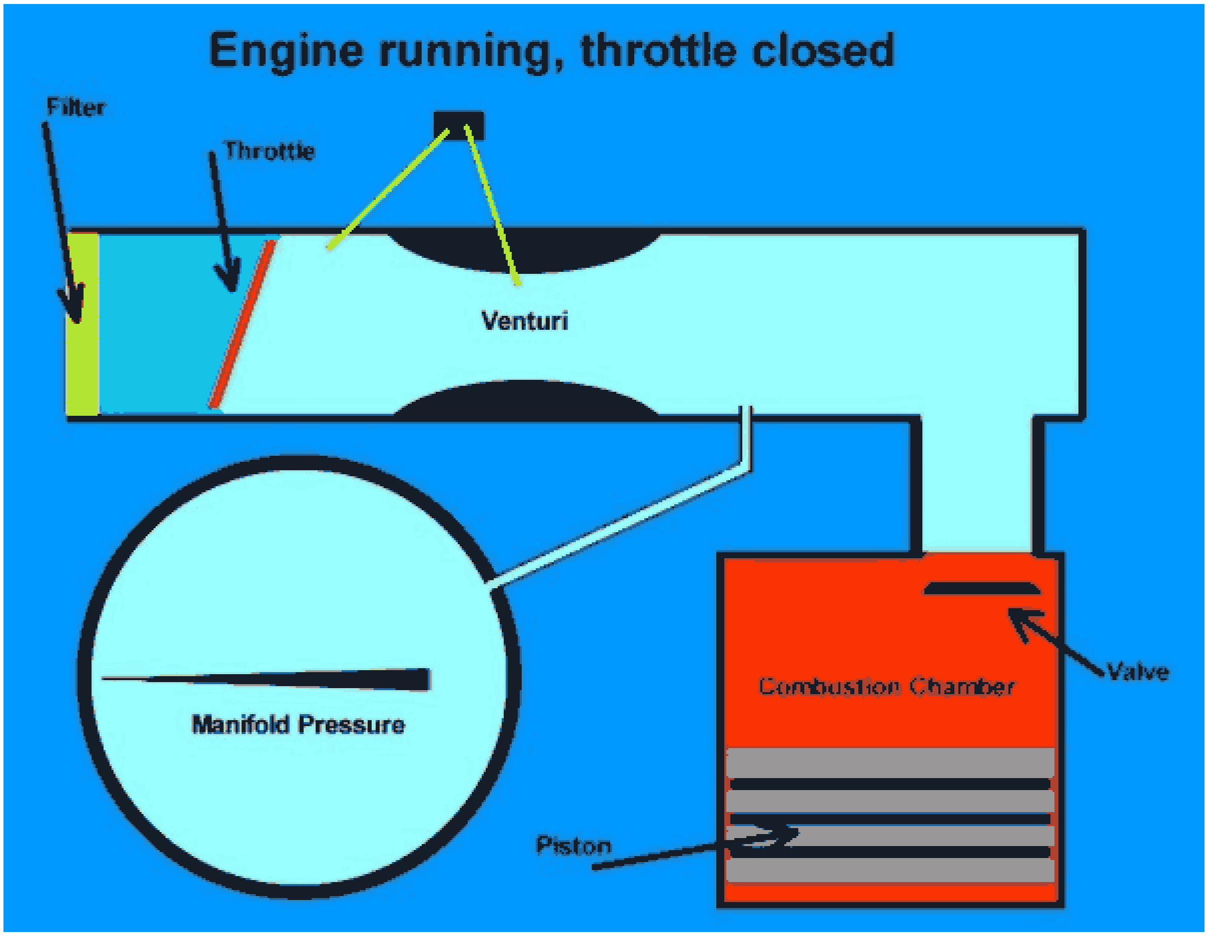
See it there, in the graphic, the narrow part of the air path? When the parcel of air comes in and passes through that restriction, it has to speed up to get all the molecules through the narrow spot. When it speeds up, our old friend Bernoulli says the pressure drops, right? Then the air expands again, returning to the same pressure it had before entering the venturi; nothing lost, nothing gained. But if we measure the <u>difference</u> between the air pressure just before the venturi and the air pressure right <u>in</u> the venturi, we can tell how much air is flowing through the venturi. That's the sole purpose of the venturi: It just creates a pressure differential within a given stream of air so we can measure the mass airflow! A very clever trick!

This venturi method is used for carbureted engines (including most of the big radials) and for injected Lycomings equipped with the Bendix/RSA fuel injection system. TCM does it a little differently on most of its fuel-injected engines: Fuel flow is dependent on simple throttle and mixture control position, engine RPM, and for some, altitude compensators.

These are subjects for later columns.

Gentlemen (And Ladies), Start Your Engines!

Ok, enough talking about an engine that isn't even running yet, let's crank it up.



In this graphic, I've left the throttle fully closed, which should give us minimum idle RPM. There's only a very small crack through which air can flow, so relatively little air can move into the system.

What Moves The Air?

This is the key point in this whole column.

In a normally-aspirated engine, the only thing that can move air through the induction system is the piston, traveling downwards, with the intake valve open! The piston sucks the air in, past the filter, past the throttle, past the venturi (on those engines so equipped), through the induction plumbing, and into the cylinder. The force to drive that piston down is supplied by either another piston on a power stroke, or the airflow past the prop in a dive with low power.

It should be clear from this that the intake system of any normally-aspirated engine is nothing more than a vacuum pump! With the throttle plate closed (throttle lever fully retarded), the piston pulls (sucks) really hard, but simply can't move much air through or past the closed throttle. The engine is literally starving for air. What happens to the manifold pressure? Why it drops, of course, actually showing substantial suction (in other words, a lower pressure than the outside air). In most engines, idle MP will be around 12 inches or so, less than half the sea-level pressure. To look at it another way, the atmospheric pressure in the intake system (downstream of the throttle) of an idling engine at sea level is somewhere up around 20,000 feet. Thus the answer to one of the quiz questions: The most stress on an intake pipe is at idle, because it is trying to "implode." Of course, we're talking about only 8 PSI difference or so, and even a light aluminum pipe will take that with ease, so it's not a problem. You wouldn't want to use a soft rubber hose for an intake pipe, though!

If we could turn the engine fast enough, if the cylinders had perfect compression, and if the throttle plate could close off the induction system completely, we could create a perfect vacuum, which would show a manifold pressure of zero. Since all the numbers on the MP gauge are referenced to this theoretical perfect vacuum, we say that the MP gauge shows "Absolute Pressure."

Note the color shades in my graphic, dark blue for ambient air pressure, a little lighter for slightly less pressure behind the filter, and much lighter for the very low pressure air behind the closed throttle plate.

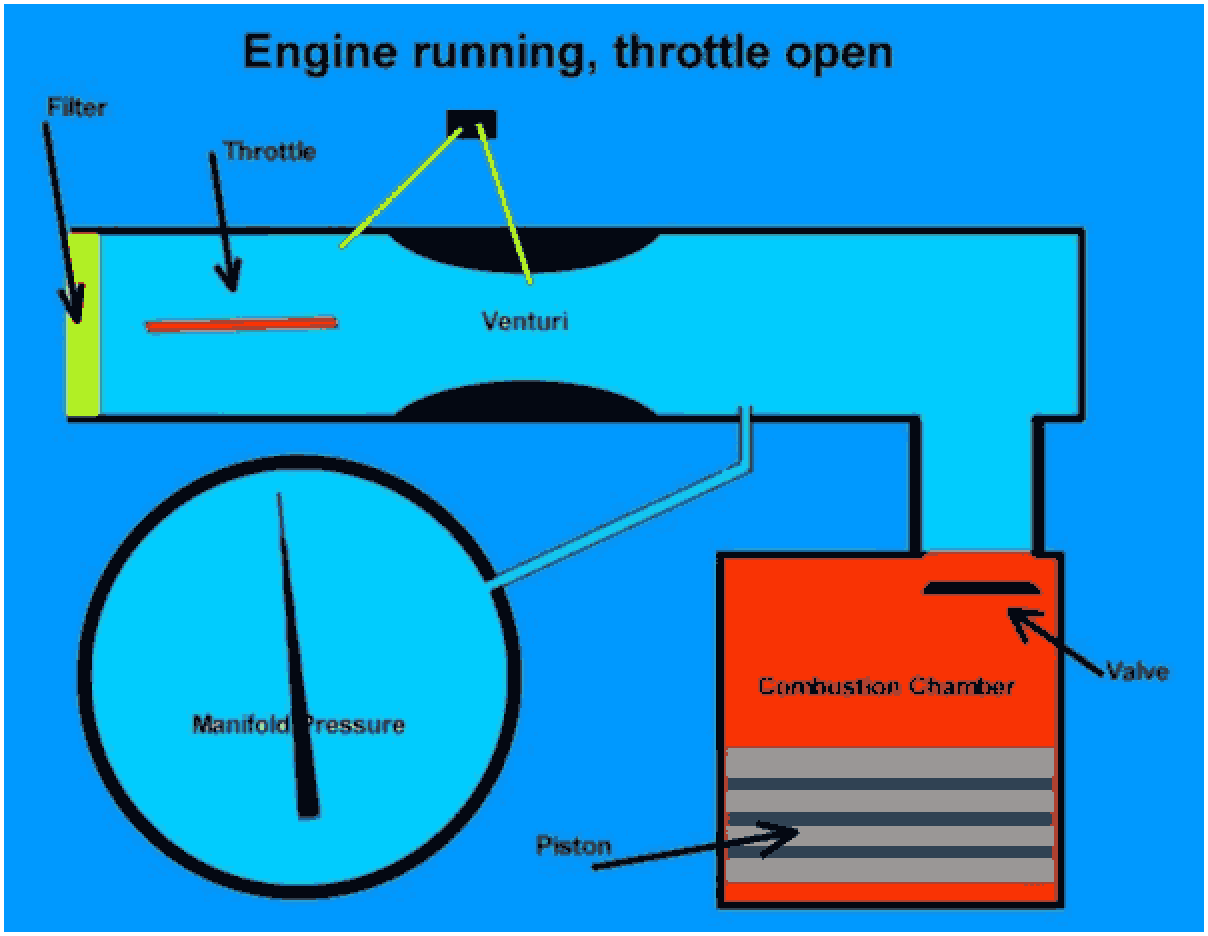
I'm Hungry, Mom!

What we have at idle is an engine that wants to run, but is simply too starved for air to do so. Since there's very little air moving, there's also very little fuel. It is literally wheezing for breath, and on some internal combustion engines, you can hear the "suck." Take the air filter off a car engine, and start it up, to see what I mean.

Suppose an anti-aircraft burst blew off the front end of that system in the picture, taking away the filter, the pipe, and the throttle assembly. What would happen? Well, if the venturi were still there and working, the engine would instantly go to full power. If that shot also took off the part of the system that contained the venturi assembly, the engine would quit (no differential pressure, no fuel). Unless it was an injected Continental, of course.

Balls To The Wall

Finally, we look at the same intake system, engine running at full throttle.



The engine can now get all the air it wants, with the only restrictions being the filter, the small area of the wide-open throttle plate (edge-on), and the turns in the ducting on the normal engine. Usually, those factors will cost you about an inch of MP, or a bit less. This is the answer to another quiz question as to why you'll see about an inch loss in MP during a full-power runup, just before brake release. During the takeoff and early climb, as the speed increases, a little bit of this loss is regained due to "ram effect" as the speed of the airplane literally rams more air into the induction system's air intake. At high airspeeds, some engines actually gain a little manifold pressure over ambient due to this ram effect.

Another key point. The intake system we're looking at has no idea what is taking place on the other side of that intake valve in the combustion chamber. It doesn't matter if there's "fire in the hole," or if the prop is windmilling in the breeze because an airline captain is talking nearby and pumping out the usual hot air, or the airplane is diving with the fuel shut off, engine not even running.

If that engine is turning for any reason, the pistons are hopping up and down, and every time one goes down with the intake valve open, it's sucking more air in. If the throttle plate is closed, it's sucking against resistance, creating suction that shows up as low MP; if the throttle is open, it's not blocking the airflow so manifold pressure remains equal to outside ambient (or perhaps an inch less due to unavoidable restrictions in the induction system).

Rule #1525

(Why Rule #1525? I don't know, aviation is full of rules, and this one is hardly the most important, so I picked #1525. Rule #1 is "Don't hit anything," Rule #2 is "Don't do nuthin' dumb.")

The rule: Manifold pressure depends on ambient pressure, the position of the throttle plate, and the speed at which the pistons are moving up and down. Manifold pressure does **not** indicate "power," unless other things are taken into account.

For a silly-but-true example, take an engine that is not running, and lift it from sea level to 18,000 feet. If the MP is 29 inches at sea level, it will be about 14.5 inches at 18,000. The change in MP is entirely due to the reduction in ambient pressure at altitude. Did the engine's power output change when the MP went from 29 inches to 14.5 inches? No, of course not -- it's zero either way.

Now a real-world example: Assume you're cruising at some low altitude (say 4,000 feet), throttled well back to about 20 inches MP and 2,000 RPM. (Remember, this means the throttle plate is somewhat cocked, restricting induction airflow.) Now reduce the RPM to 1,200 without changing anything else, and you'll see the MP rise sharply. Why? Simple: The ambient pressure hasn't changed; the throttle plate hasn't changed; the only thing that has changed is the speed at which the pistons are pumping the air. Since they are moving much more slowly at the lower RPM, they are not sucking nearly as hard -- not creating as much of a vacuum -- so the MP goes up, towards ambient pressure. The natural extension of this experiment is to reduce the RPM to zero, when the MP will rise all the way to outside ambient pressure (about 25 inches at 4,000 feet).

In this example, the RPM has been lowered. The pistons are sucking far less air, the speed of the air going through the intake is less and fuel flow is less. This means there is less power being developed, in spite of a much higher MP! You will also see the airspeed drop off sharply, confirmation of "less power."

Conversely, start once again with our example of cruising at 4,000 feet, 20 inches MP and 2,000 RPM. Now run the RPM up to 2,700, leaving everything else unchanged. Now the pistons are pumping much faster, drawing more air in past the (partially open) throttle plate. That creates more suction -- a lower pressure in the induction system -- which will show as a lower MP. There will be more fuel flow, and you'll be producing more power at lower MP. (This is complicated by prop efficiency, so give me a little room here.)

Back To Full Throttle

The foregoing examples were all with the throttle plate cocked at the angle that gave us an initial cruise power setting of 20 inches MP, and 2,000 RPM.

What if we push the throttle in to the full-throttle position, changing nothing else? By opening that throttle plate, ambient air (plus a little ram effect, minus the resistance of the air filter) is allowed to flow rather freely into the induction system, so the MP indication jumps up to ambient pressure, about 25 inches. This causes more fuel to flow, and the engine produces a lot more power.

Now, at full throttle, let's vary the RPM again. Run the RPM up to 2700. The pistons are pounding up and down much faster, so they are pulling a lot more air in. But what happens to the manifold pressure? Essentially, nothing. Since there is no restriction in the intake, ambient air pressure is free to enter, no matter how fast the engine wants it, or the pistons suck it.

(If you have trouble with this concept, think of your own breathing. If you open your mouth wide, and take a slow breath, there is no resistance, and if you take a big quick breath, there is no resistance. Very little difference, anyway. If you suck air through a soda straw very slowly, there is also no noticeable resistance. But just try and suck a big breath of air through that straw, and you'll know how that poor intake system feels at partial throttle and high RPM.)

In this example, still at full throttle at 4,000 feet, you should see about 25 inches and 2,700 RPM. The mass airflow is way up, so is the fuel flow -- and you're movin' out!

Don't Try This At Home, Folks!

This next test is one you really don't want to do with your engine, because at high power settings and low RPM, your engine may detonate, even at very rich mixtures. But it's a useful thought experiment. (I'll cover detonation in a later column.)

From full throttle at 4,000 feet, 25 inches MP and 2,700 RPM, we reduce the RPM back to 1,200, changing nothing else. (Again, please don't do this!) The pressure in the intake is already at ambient pressure, so it can't go any higher, nor can it go any lower. The pistons are still pumping, but at less than half-speed, so they're not pulling nearly as much air through. The MP will not change appreciably. (A few pilots report a very slight rise in MP, which is probably because there is less resistance to the slower-moving air at the filter screen, but essentially there is no change.) Because of the dramatic drop in RPM and airflow, the fuel flow drops too; meaning much less power is being developed, with no change in MP.

(Testing done since this column was written has demonstrated that the risk of detonation in the above exercise is virtually non-existent in normally-aspirated engines. This exercise is somewhat abusive of the engine, but will probably not harm anything.)

The Induction Air Filter

What's the filter for, anyway? These engines pump vast quantities of air. An IO-550 at full power pumps over 400 cubic feet of air per minute, a small roomful. Do that for a few hours, and you'll also pump a fair amount of trash, grit, and dust through the engine, and that's not good for the finely-machined surfaces. So an air filter catches the majority of that stuff, at a cost of perhaps an inch of MP at high power (assuming the filter is clean). Note that the filter has exactly the same effect on MP as the throttle plate when slightly closed.

A dirty filter, on the other hand, could cost you many inches of manifold pressure. So pop for a new one every once in awhile, please? They're cheap, even by airline pilot standards.

It seems intuitive that a dirty air filter is "bad" because it restricts airflow to the engine. What doesn't seem to occur to many people is that a throttle that is only partially open is exactly the same as a very dirty air filter! It doesn't matter how you restrict the air, the end result is the same: less power available.

All else being equal, any engine will be more efficient if operated at full throttle. If you don't want all that power (or fuel flow), use a lower RPM, a leaner mixture, or both. Of course, full throttle makes it tough to get slowed down in the traffic pattern, and it can be tough on the brakes while taxiing, so the throttle can come in handy now and then. But it's best to avoid using it during climb and cruise, and I'll be talking more about this in another column.

The Whistling Engine

What's that whistle at idle power I asked about in the quiz? You should be getting an idea by now. It's probably from an induction leak, and the low pressure in the pipe is sucking air in from outside through the leak. Good reason to take a break, open up the cowling, and have a look.

What will happen if you go flying with an induction leak? Well, think about it. There is air sneaking into the engine that has not been "measured" by the venturi, so the fuel flow is unchanged. More air, same fuel, makes a leaner mixture in the cylinders fed by the leaking intake pipes, so that cylinder (or cylinders) will be running leaner than you intend, unless the throttle is fully open. On the ground, you'll probably see an abnormal idle, perhaps roughness caused by one cylinder running too lean, or not at all.

I don't mean to suggest that all induction leaks will produce an audible whistle. They won't. But there's another, better way to detect an induction leak. Have you figured it out? What will such a leak do to the MP indication at idle? Right! Less suction, higher MP. So if you're used to seeing 12 inches of MP at idle at your home airport and one day you see 15 inches instead, suspect an induction system leak.

The Rest Of The Story

Manifold pressure is only one part of the story: We still have props and mixture to go. Not to mention turbos. Stay tuned.

Be careful, up there!

April 19, 1999

Pelican's Perch #16: Those Marvelous Props

In this month's column AVweb's John Deakin moves from the black knobs (MP) to the blue ones (RPM). He starts with a history lesson about how we got from windmills to fixed-pitch propellers, adjustable and controllable ones, and ultimately to constant-speed props. John then explains how they work, why they work the way they do, and how you can tell if they're working the way they're supposed to. He even answers that age-old conundrum: how many times should you cycle the prop at runup?

By John Deakin

Like manifold pressure (see my previous column, "Manifold Pressure Sucks!"), propeller systems are often not well understood by those who depend on them. But there is no part of the airplane more critical, or that endures more stress and abuse. We really ought to know more about our props in order to get the best service and performance out of them. This is even more important on the feathering props found on twins, and of paramount importance on the big radials where prop systems become much more complicated and have many more failure modes. When something goes wrong with these systems, failure to take prompt and correct action with them can be deadly. A DC-3 was lost with all aboard in Holland just a couple of years ago, probably from simple ignorance of a common failure mode.

For most mechanical failures on aircraft, it is possible to "check the book," run a checklist, or carefully consider what action should be taken. In fact, most emergencies need to be handled slowly and thoughtfully. But prop failures rarely allow this privilege, and usually need to be handled promptly and correctly, from memory and from knowledge.

NOTE: *I am indebted to the Hamilton Standard Division of United Technologies, Hartford Conn., for their kind permission to reprint and use their wonderful little 60-page booklet "Prop to Pilot" first published in 1948. Many of the pictures in this column have been scanned from that booklet. It does a marvelous job of explaining the old props on big airplanes. This booklet is no longer in print, but I have made copies which are available to seriously-interested AVweb members. Many of the principles explained in the book are applicable to modern small props on general aviation aircraft, but the mechanical descriptions can be very different. For warbird/antique aircraft folks, this booklet is a must. If you'd like a copy, check out www.flybyeknightpress.com page for ordering details.*

I'd like to get into this subject via the back door, so to speak, by starting with a common windmill. If you put one of these in a breeze, it will spin. Moreover, the speed of the wind directly affects the speed of rotation. Obvious, you say? Well, yes — but humor me, there's a point.

There are major similarities between the windmill and that big buzz saw hung on the front of your airplane. Even with an aircraft engine shut down in flight, you can vary the RPM of a fixed-pitch prop by changing your airspeed. We call this "windmilling," of course.

A Little History

All the early props were fixed-pitch, and there was always a lot of discussion among pilots over just what that pitch should be. There were "power props," "climb props," and "cruise props." For power, they needed a prop that would turn pretty fast right from the beginning of the takeoff roll, but such props would increase RPM with increasing airspeed (like the windmill), soon going out of RPM limits, and losing efficiency, too.

Put a "climb prop" on the airplane, and you wouldn't get as much RPM early in the takeoff roll. Acceleration would be slower, making the takeoff roll somewhat longer, but you'd see full RPM at the normal speed for climb. At cruise speed, the prop (and the engine, of course) would tend to overspeed (windmill effect again), and the throttle would have to be pulled back to avoid going over redline. This imposed a limit on cruise power, of course. Finally, a "cruise prop" would turn just about the right RPM at normal cruise airspeed. This did wonders for gas mileage, but would not get the airplane off without a very long ground run, and the RPM at the start of the takeoff would be very low.

We still see this today on the small aircraft used for trainers. Most of them are equipped with "middle of the range" fixed-pitch props, neither optimized for takeoff nor for cruise. The only reason these work as well as they do is because the speed range of the aircraft they haul around is so limited, from about 50 to 100 knots, and runways are more than adequate, having been built for larger aircraft.

<u>With a fixed-pitch prop, RPM varies with engine power and airspeed.</u>

Please be sure you understand this concept before going on. The engine power concept is intuitive, but "the windmill effect" is sometimes not. This is also often spoken of as "prop load" because with a large blade angle, the prop "loads" the engine, slowing it down. With a smaller blade angle, the prop "unloads" the engine, allowing the engine to speed up.

Variable Pitch Props

It didn't take long for early aviators to invent a "Ground Adjustable" prop. With only a few tools, working directly on the prop hub, the barnstorming pilot could set his prop for "power" to get out of a small farmer's field and do local rides at slow speeds, or perhaps tow a banner to advertise something. For the cross-country flights to the next town — or for racing (popular in those days) — the pilot might want to set a better pitch for cruising. This prop is nothing more than a fixed-pitch prop in-flight, so again, power and airspeed control RPM directly.

Next came the "controllable pitch" prop, a primitive device at best, but an improvement. It didn't require tools, and the blade pitch could be changed from the cockpit in flight. The pilot directly set the pitch angle of the prop blades, so at any given pitch setting, RPM still varied with power and airspeed.

Now I wasn't there (contrary to the opinions of some), but I'm sure it wasn't too long before pilots were whining about how much trouble it was to control the prop. Pilots are never satisfied. Make their jobs easier and they want more money. Cut their required flying hours and they whine about the loss of *per diem*. But, I digress.

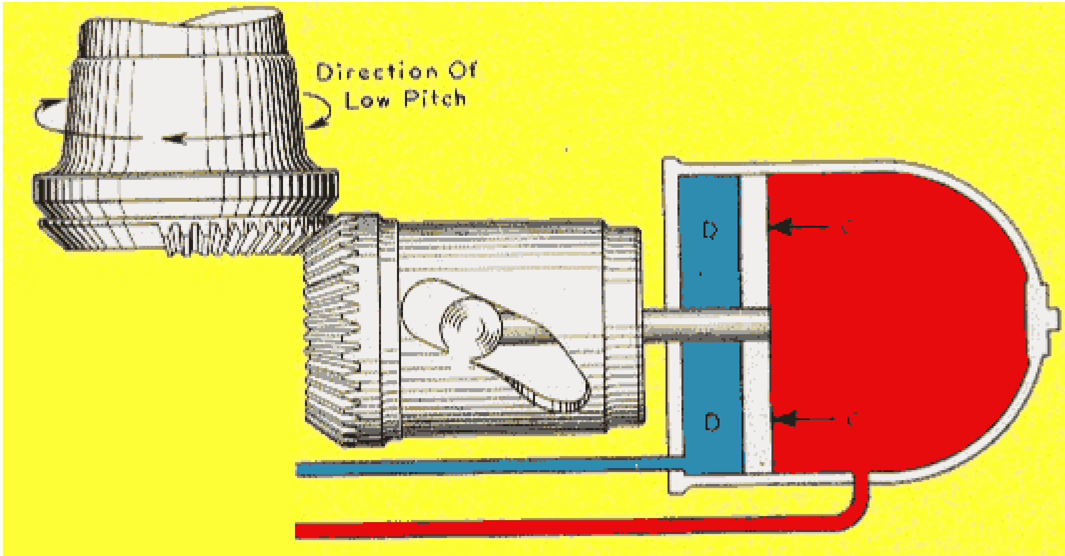
It is important to note the concept here. With this old prop, the pilot sets the pitch angle of the blades directly. Once the pitch is set, RPM remains a function of power and airspeed.

The picture below shows a rough idea of a controllable pitch prop, with our hero the pilot manually setting the pitch angle. If anyone had bothered, they might have marked the prop control with settings in degrees, perhaps 15 degrees for the flattest angle and 30 degrees at the other extreme. Some of these would be set to one extreme for takeoff and climb and the other extreme for cruise, for there were no manifold pressure indicators in those early days.

A number of solutions were tried to reduce the pilot whining ... er, workload, with varying degrees of success. Some props used counterweights to balance aerodynamic forces so that if the prop were under a load, the blades would flatten out automatically, increasing RPM and power. If the pilot increased the airspeed or reduced the power, the load would drop, the blade angle would increase, and the RPM would drop. This automated the process somewhat, but left the pilot with no options: The prop pretty much did what it wanted to do. These old self-adjusting props can be distinctly odd to fly, as the prop will do its own thing, changing pitch (and RPM) when it wants to. Most of them worked pretty well, though.

Constant Speed Props

Finally, the constant-speed prop was developed. The remainder of this column will be confined to this type, for this is what we see on the vast majority of propeller-driven airplanes today. Again, there are many variations in the actual mechanism. Some — including most of the Hamilton-Standard props used on radial-engined aircraft — look something like the diagram below, particularly the gearing between the blades and the rotating sleeve. A few props have used an electric motor right in the prop hub to rotate that sleeve, but the vast majority uses some combination of engine oil pressure, springs, boosted oil pressure from a governor, air pressure, or aerodynamic loads to move the mechanism that changes the pitch on the blades.



An oil-operated constant-speed propeller contains a mechanism to convert movement of the piston in the propeller dome into blade pitch changes. In the Hamilton-Standard design pictured above, a roller and cam arrangement rotates a central sleeve in the hub, which is coupled to the base of the blades by bevel gears. In the picture above, oil pressure is used to drive the piston back and forth within the prop dome, which drives a cam roller, which rides in the slot in the sleeve, causing the sleeve to rotate. Bevel gears on the sleeve and at the base of each prop blade translate rotation of the sleeve into pitch changes of the blades. This particular picture shows a feathering prop, with the cam roller in the normal range. The angled portion of the slot to the right and down is the feather range, and requires extra high pressure from a supplemental pump, to gain enough mechanical advantage to drive the cam "over the hump." This is a common installation on a big radial engine, like the superb Pratt and Whitney R-2800.

The Hartzell and McCauley props used with most flat piston engines and many turboprops use a slightly different mechanism in which the piston changes the blade pitch by means of a pushrod-and-bellcrank arrangement instead of bevel gears. (The pushrods are actually called "pitch links.") This design allows for a lighter and more compact prop hub, but the principle of operation remains the same.

The normal aerodynamic force on any airfoil tends to pitch it down (to a lesser angle of attack). Props are no exception, since they are rotating airfoils. Aerodynamic forces tend to drive all props to the flat pitch position.

A NOTE ABOUT TERMINOLOGY:

This is a good time to mention that "flat" pitch is the same thing as "low" pitch (a low blade angle, in degrees), or as our British friends say "fine" pitch. This generally implies a higher RPM, all else being equal. I find it very easy to get confused (and to confuse others!) if I don't think very carefully when talking about prop pitch, because "Low Pitch" goes with "High RPM." You need to listen very carefully, too!

The opposite is of course "high" pitch (British "coarse" pitch). Again, easily confused, as "High Pitch" generally implies "Lower RPM."

In most of the big radials both normal "pitching moments" of the blades and normal engine oil pressure drive the prop towards the "Low (flat) Pitch" position. On such installations, there must be a force that is capable of overcoming this tendency to "go flat" or we'd have no control at all. This force usually comes from oil pressure from a prop governor, which is capable of supplying much greater oil pressure to the other side of the piston in the prop hub.

The constant-speed props used on most <u>single-engine</u> general aviation aircraft use a very powerful internal spring to drive the blades to flat pitch, with governor oil pressure used to oppose that force.

In either case, a governor failure causes the prop simply to go to full low (flat) pitch, whereupon it becomes just another fixed-pitch prop (of the "power" type).

By contrast, the full-feathering props used on most general aviation <u>twins</u> work differently — almost the exact opposite, in fact. The hub of such a prop contains a very powerful spring (called the "feathering spring") that drives the prop towards "high pitch" ("low RPM" or "coarse pitch"), while governor oil pressure (and pitching moments) oppose this. This means that a governor failure — or loss of oil pressure — in a light twin will drive the prop towards low RPM (high pitch), and right on into feather, which is nothing more than extremely high pitch. The theory is that with a loss of oil pressure due to engine or governor failure, you'll want the prop feathered in order to keep flying on the other engine.

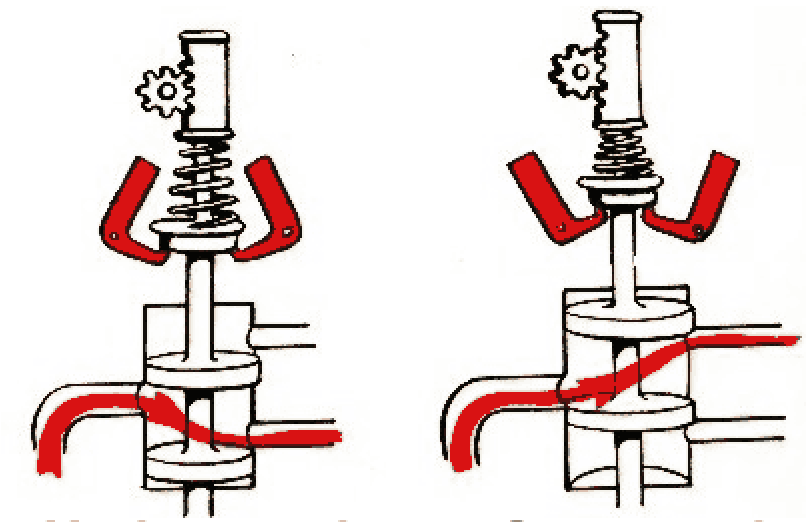
Why don't these full-feathering props drop into feather at shutdown, when the oil pressure goes away? Well, in fact, the ones used with free-turbine engines like the Pratt & Whitney PT6 do exactly that — take a look at a King Air or Caravan parked on the ramp and you'll see this clearly. But having the prop on a piston engine go into feather at shutdown would be very tough on the engine at the next startup. There would be so much air resistance with the blades feathered that it would be difficult to keep the engine running until enough oil pressure built up to bring the prop back out of feather. It would probably be hard on the engine, too, for it would have to develop considerably more power while still cold, before there is sufficient lubrication for the bearings. This would cause a lot more metal-to-metal contact before the oil starts circulating.

Consequently, the full-feathering props used on piston twins and certain turboprops are designed with a system of centrifugal latches and pins that lock the blades in a medium-pitch position when the RPM drops below 600 or so, preventing them from going into feather at shutdown. In the event of an in-flight loss of oil pressure, however, windmilling action keeps the prop RPM high enough that the centrifugal latches don't come into play and the prop fails in the feathered position. Pretty clever.

Take a walk on any general aviation ramp, and look at the constant speed props. You will generally see the singles sitting at rest with a very flat pitch (usually around 15 degrees), the piston twins with a very coarse pitch (usually around 30 degrees), and most of the turboprops in full feather.

"What's up, Guv?"

To this point, all we have are variations on a common theme, and some mechanical descriptions of how to change the pitch of a prop. Now we come to the clever device that makes it easier for the pilot (remember, the whining increases, though) and allows him to simply select a desired RPM. This device is the prop governor, and here's a very simple "concept schematic" of one type of this hard-working device.



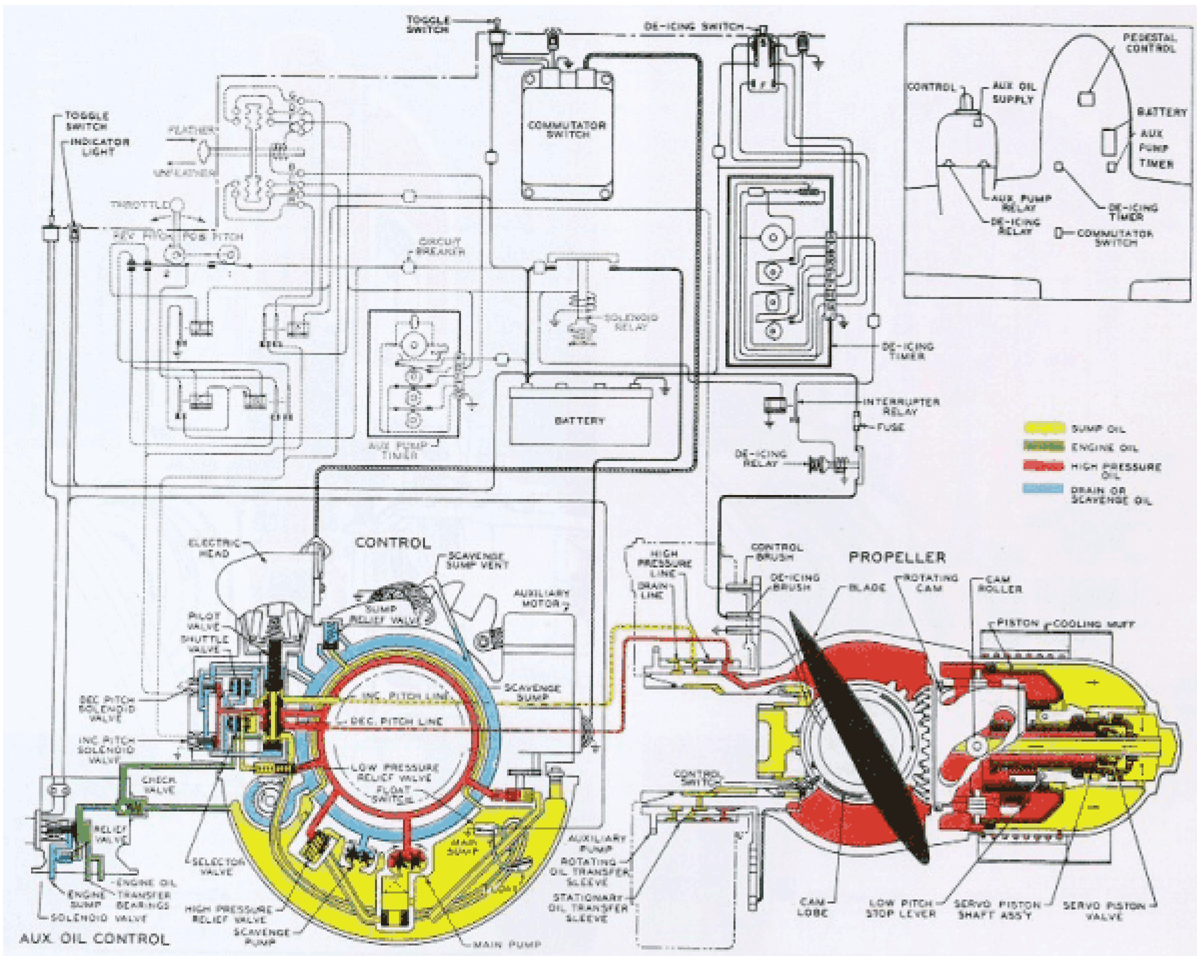
Prop governors are gear-driven by the engine, so the faster the engine turns, the faster the governor turns. Flyweights work against a spring, and the prop control in the cockpit adjusts the loading on that "speeder" spring. If the engine is turning faster than the desired RPM, centrifugal force flings the flyweights out against the spring pressure, which moves a valve that allows oil to flow in the proper direction to move the prop blades to a greater pitch. If the RPM drops below that desired, the flyweights move in towards the center, moving the oil valve that allows oil to flow as needed to decrease the blade angle, increasing RPM. When the RPM exactly matches the setting by the pilot, the flyweights exactly balance the spring pressure, and shuts off all oil flow to the prop.

Most governors also contain a high-pressure oil pump to boost engine oil pressure (which is typically around 50 PSI) up to the levels needed to control the prop (often around 200 PSI).

In reality, the flyweights are constantly making tiny movements to keep the RPM at the desired value, either pumping little squirts of oil to the dome, or letting a little oil out. Once again, there are many variations here. Some systems will pump oil to drive the blades one way, or allow that oil to dump into the crankcase, allowing the spring to push the piston the other way.

For general aviation singles and twins, the very least you should know is what will happen with a failure. For singles, the prop will generally go flat. For twins, it will probably feather. Check your POH, and ask your mechanic about the details for the airplane you fly. You can't know too much about props!

For big radials, there are a number of additional sub-systems and failure modes. If there is sufficient interest, I might do a future column on them, but I doubt there are more than a few people reading this with any interest in these "dinosaurs." Just for fun, here's what one looks like. This is a Hamilton-Standard, Constant-Speed, Full-Feathering, Reversing, Auto-Feather, Step-Head Motor Controlled, Heated prop, as found on the Martin 404, an early-fifties airliner operated mostly by TWA and Eastern. The governor is similar to the one I've described, but instead of being controlled by a push-pull cable, there is an electric motor on top of the governor that sets the speeder spring compression, and this motor is toggled with switches in the cockpit. As you might imagine, this adds considerably to the failure modes, since an electrical failure deprives the crew of all prop control, it will simply try and maintain the last RPM requested. This system takes up major portion of the ground school I teach on this airplane!



Reversing Propeller Operating Diagram — Underspeed Condition

Bringing It All Together

The airplane you fly is probably sitting on the ground somewhere as you read this, at rest, with the prop control lever fully forward. What would you expect to see? If it's a single, the prop should be in full flat pitch (spring-driven). We might say, "It's on the low-pitch mechanical stops." If it's a twin, the spring will be pushing the prop toward high ("coarse") pitch, but the little mechanical pins will be engaged, preventing the prop from feathering. This may or may not coincide with the prop pitch setting when the governor commands "full high pitch" (as opposed to "feather," which is even higher pitch). In these full-feathering props used on twins, there is no mechanical high-pitch stop. Most props will be at about 15 to 20 degrees at "Low Pitch", and about 30 degrees at "High Pitch." This difference can be seen clearly just in looking at the prop.

If the prop lever is fully forward on either the single or twin, it is "requesting" full takeoff RPM from the governor, probably something between 2,400 and 2,700 RPM. This prop control setting fully compresses the speeder spring, and since there is no centrifugal force holding the flyweights out with the engine at rest, they will be fully "in," porting oil as necessary to flatten the pitch and increase RPM. Of course, without oil pressure, nothing is happening, but the governor is trying!

Startup

Now, ladies, start the engine and bring it up to about 1,000 RPM.

A side note on one of my pet peeves here, if I may? If there is anything that reveals a rookie to me, it's the pilot who starts any recip and lets the RPM go roaring to some high figure. I see and hear some of these airplanes started, and it sounds like the engine instantly goes to 1,800 RPM and then it stays there for a time. The parts are cold, the bearing surfaces have hardly any oil film to keep them apart, there is no oil pressure at first, and you're destroying an engine.

Some powerplant experts suggest that 90% of all piston engine wear takes place during that initial few seconds of engine run, and that's <u>when it's properly done</u>. Once the oil is warm, and at full pressure, there should be virtually no metal-to-metal contact anywhere in the engine. Some ground-bound recips that run continuously — the ones that operate "walking beam" pumps in oilfields, for example — have run for years without stopping, yet show very little wear when torn down. Starting is <u>hard</u> on engines, especially when cold. You need about 800 to 1,000 RPM to get the oil pressure up and to provide some "splash" lubrication on those engines with wet sumps, but <u>please keep the RPM down to about 1,000</u> until the engine has a chance to get the oil circulating. <u>NEVER</u> start a recip with the oil temperature below about 40°F.

I'd also like to point out that almost every time I see one of these rookies do the high-RPM start trick, there is almost always someone on the receiving end of their prop blast, and not very happy about it. <u>THINK</u> about your prop blast, and minimize it, when you're on the ground! Think where the dust cloud will go, too.

[Flame off.]

Okay, we've started the engine, and the oil pressure comes up. In the single, the oil doesn't do anything at all for the prop yet, because with the prop lever fully forward, it's calling for full RPM, and the prop is already as flat as it ever gets. In the twin, the oil pressure will drive the prop blades off those latch pins to full low pitch (flat). Once oil pressure is up in both the single and the twin, the prop blades will be on the low-pitch mechanical stops. RPM is, of course, controlled directly by power, since there is no airflow on the ground to "windmill" the props.

Runup

Most Continental direct-drive engines are run up at 1,700 RPM, and most Lycomings specify runup at 2,000 RPM. There is no magic about 1,700 or 2,000 — it's more tradition than anything else — but such mid-range RPM settings do provide a little room to exercise the prop, and also provide a modicum of power to check out the ignition system. The tests and checks will be just as good at 1,500, 1,800 or 2,100, so there is no real need to be precise in setting exactly 1,700 or 2,000 for the runup.

At runup RPM, the prop lever is still fully forward, the prop governor is still calling for redline (2,400 to 2,700 in most cases), and the prop blades will still be on their low-pitch mechanical stops. Now, we pull the prop lever back. It doesn't really matter how quickly or how slowly you do that, but for our purposes here, let's say you do it very slowly, perhaps an inch at a time, stopping along the way to see the results. The first inch will reduce the speeder spring pressure, and perhaps it will call for 2300 RPM. Since runup RPM is lower than this, the flyweights are still fully "in" and the system is still trying to increase the RPM by driving the prop blades "flat." The blades are still on the low-pitch mechanical stops, and the governor still sees an "underspeed" condition.

Pull the lever back some more, to the point that might call for exactly runup RPM (1,700 or 2,000). Now, at last, "something happens." Moving the prop lever that far will reduce the speeder spring pressure enough that the centrifugal force on the flyweights is "enough" to move them "out" to the "balance point," where the centrifugal force on the flyweights is exactly balanced by the speeder spring pressure. Still, nothing happens at the prop, because the governor is calling for 1,700 (or 2,000), and we've got 1,700 (or 2,000). The blades will still be on the mechanical low-pitch stops, but barely so.

Finally, pull the lever all the way back. This further loosens the pressure on the speeder spring and runup RPM is now more than enough to make the flyweights open out. We call this an "overspeed condition," as the prop is (momentarily) turning faster than the governor wants it to. The flyweights open up, porting high-pressure oil into the the prop dome (or for twins, letting oil flow out of the dome), and at last, the prop blades come off the low-pitch mechanical stops and move towards the "coarse" position. Since we have changed nothing but the prop control, this will reduce the RPM, proving the system works as advertised. Many POHs will specify what the lowest RPM should be on runup, and this is important, as it shows "full range." If your POH doesn't list this figure, check it out for yourself, and note it for future runups. The prop does not necessarily go all the way to the high pitch stops, it only goes far enough to satisfy the governor.

For many twins, moving the prop lever fully aft not only reduces the "desired" RPM, but will cause the prop to move towards feather. This should also be checked (very briefly), in accordance with the POH. In most cases, you should avoid allowing the RPM to decrease below 1,200 or so to prevent the anti-feather latch pins from wearing out.

(Note that pulling the prop lever back in "steps" is only for the purpose of this discussion. In practice, it's one smooth motion.)

How many times should you cycle the prop? If the RPM drops smoothly and properly, once is enough. The fresh oil will probably cause the piston to move a good deal and when it comes back to the low pitch stops, most of the "old" oil will be pushed out. If you really want to feel good, do it twice, to get even more of that "old" oil out of there. Three times is gross overkill, in my opinion, but a lot of people do three times, or more. In reality, there are tiny bleed holes that allow a constant flow of warm oil to both sides of the prop piston, so even if you take off with cold oil in there, it will quickly be replaced with nice slippery warm stuff. On some of the big old props on the radials, in extreme Arctic conditions, the oil would congeal faster than the bleed ports could replace it, but I doubt you'll find any modern props with this problem. I should note for completeness that many of the props on the big radials might require many more cycles to achieve a smooth RPM drop when cold. In freezing temperatures, it may take up to ten cycles. There's a lot more to the mechanism, and a lot more oil involved.

Takeoff

Runup complete, we clear the area, taxi onto the runway, set full power, and go. You should, by habit, check the RPM, manifold pressure, and fuel flow (if available) on the roll. A glance at the rest of the engine indications is a good idea too, but these three are primary. If you've read my previous column you should know what is "normal" for manifold pressure on any takeoff. On most of the big-bore flat engines by TCM and Lycoming, it is vital to see full redline fuel flow at full power at sea level. A hair over is better than a hair under. (I plan to cover this and other mixture-related stuff in my next column.)

(As engine monitors have become much more common since this column was written, we also strongly suggest including the graphical display in the scan right after full power is set.)

What about RPM on takeoff? At some point, you must see full redline RPM, plus or minus very little, perhaps 50 RPM or so (check your manual). You may see this early in the takeoff roll, or it may take some speed to bring it up. On my airplane, full power, sea level, holding the brakes (bad idea, this is a test only), I'll see about 2,600 normally, and this will build quickly after brake release to about 2,740, a bit over redline. (I'll adjust this at the next opportunity.) I have the Horizon electronic tach — which is extremely accurate — so I'm confident in those numbers.

Incidentally, normal mechanical tachs are much less reliable and far less accurate. When they get out of calibration, the errors tend to be on the downside, which means that the engine is turning higher RPM than you think it is. If your airplane has a mechanical tach and it's not making redline RPM on takeoff, be sure your mechanic checks the tachometer calibration with an electronic tach checker before making any adjustment to the high-RPM stop on the prop governor. There's a good chance that your prop is making redline after all, but your mechanical tach is simply reading low.

Returning to our takeoff, you should now be starting to understand what is happening here. At full power, brakes locked, the prop is fully flat, and the governor is calling for "more," or 2,740 (speeder spring is fully compressed, flyweights "in".) As the speed increases after brake release, the "load" on the prop decreases ("windmill effect"), and the RPM kicks up to 2,740. At this point, the flyweights move out to the neutral position, and everything is "in balance." As the speed continues to build, the RPM will rise slightly above 2,740, but the flyweights will "open up" a tiny bit, and allow oil to flow to the prop hub to twist the blades off the low-pitch stops, cutting the RPM back to 2,740. Repeating this process, it should keep the RPM right at 2,740 until otherwise set.

Immediately after liftoff, gear coming up, altitude and airspeed increasing, I'll reach over and pull the prop back a bit, perhaps two turns on the vernier control. This loosens up the pressure on the speeder spring, which allows the flyweights to move "out" (overspeed condition), porting oil to "coarsen" the blade pitch, reducing the RPM. As the actual RPM matches the "requested" RPM, the flyweights move back to neutral, returning to the "on-speed" condition.

If the airspeed continues to increase and we change nothing else, the "load" on the prop becomes a tiny bit less, the prop tends to overspeed, the flyweights correct, and the RPM returns to the RPM set.

Hitting the Stops

You will recall that when I described the "controllable" prop above, I said "the pilot sets the pitch angle of the blades directly." Contrast this with the "constant speed" prop, where the pilot sets a desired RPM, and the governor takes care of the blade angle as necessary to attain and maintain that RPM.

But there are limits. If the prop blades come to rest on either the low-pitch or the high-pitch stops in flight, the governor can do no more, and the RPM will then be controlled directly by power and airspeed once again. In effect, once the prop blades "hit the stops," what you have is just an old-fashioned fixed-pitch prop.

When might this happen? Low power plus low airspeed will do it, such as when you pull the throttle way back on short final. If the engine doesn't produce enough power to maintain the desired RPM and there isn't enough windmill effect to drive the prop, the prop blades will eventually reach the low-pitch stop while trying to maintain the desired RPM, and thereafter, RPM will drop.

Another common scenario I see is letting down at high speed from high altitude, with airspeed edging up into the yellow arc. The windmill effect will "unload" the prop, tending to increase the RPM, and the prop blades will twist to a "coarser" pitch to maintain the set RPM (I usually set 1,800 in this case). When the prop blades hit the high pitch stops, they can go no further, and the RPM will rise. Again, your constant-speed prop becomes a fixed-pitch prop. There's no harm, but it can cause concern to the unwary because it will appear the prop governor has failed. Pulling the prop all the way back, even to the full high-pitch (low RPM) position will have no effect at all because the prop is at the highest pitch it can achieve and the governor has no way of increasing the pitch further. Only a decrease in airspeed or power will bring the RPM back down to whatever is set by the prop control. At some very high airspeed, even idle power would not be enough to overcome the windmilling effect, and the prop would overspeed no matter what you did. I prefer not to investigate that, thank you very much.

A most interesting scenario is the twin with an engine failure. The classic demonstration is to set up a cruise speed, with a fairly low RPM on both engines, and cut one mixture or turn off the mags. The beginning multiengine student will assume the RPM will drop, but he'll be quite surprised to see the RPM on the failed engine remain the same as the running engine! In general, a failed engine will show no immediate changes whatsoever on any engine instrument. After some seconds, the cylinder head temperature will start down, but in most cases, the manifold pressure, the RPM, oil pressure, temperature, and other parameters will be unchanged, not helping to identify which engine has failed. Of course, if there is a fuel flow indicator, and the mixture is cut, or the fuel turned off, that will show, but the nasty old instructor will probably cover that up.

What's happening here? Well, when the power is lost, the RPM starts dropping. But the flyweights instantly move "in" (underspeed), and port oil to decrease the blade angle, towards "low pitch" or flat. Given enough airspeed, and cruise is almost always enough, the windmill effect will continue to drive the prop at full RPM, and the governor may even have to keep it from going all the way to low pitch. The prop governor has no knowledge of "power" — it senses only actual RPM, and tries to correct to "desired" RPM, but it can only do that within the limits of prop blade travel.

(Incidentally, I lied to you above. There is one engine instrument that will always give an immediate indication of an engine failure. That instrument is the EGT gauge. Extra credit if you caught this.)

Cruisin' Along

How do we set cruise RPM, and what are we trying to accomplish? Remember when talking about wings and airspeeds for "max range" or "max glide" or "minimum sink." What we are trying to do with the wing is change the efficiency by varying the angle of attack. We can go real fast, and run the parasite drag up, or we can slow down to minimize it. At some point, we will be making the "Max L/D" or the most lift we can get relative to the drag, or even slower to find the absolute maximum lift the wing will produce.

By changing cruise RPM, we are doing the same thing. A high RPM may produce the maximum power, but at a cost in drag (and fuel). Just like any airfoil, the prop has its optimum angles, too, but data on these are not readily available to the pilot, and they are often overridden by the need for the most efficient airspeeds of the airplane. But generally speaking, for any given power, the lowest possible RPM will reduce friction within the engine, and this may be the most important parameter. Some props are probably more efficient at a specific RPM.

A final thought experiment. Let us start with a feathered prop, in flight. Assume we have feathered it as a training exercise — preferably in a twin — and now it's time to restart the engine. We have enough power on the other engine to just maintain altitude and airspeed.

Feathered, the blades are edge-on to the airflow, so there is minimum drag on the airplane, and there is nothing make the prop turn. Let us fantasize a bit here, and say that we can control the pitch directly, holding it exactly where we want. (This is possible with the old Curtiss Electric props, by the way.) Now we move the prop blades just a tiny bit out of the full-feather position, just barely enough to make the prop start to rotate — maybe one revolution per hour. Think about what's happening here: The blades act just as any airfoil, with speed, and a small angle of attack. They produce just a tiny bit of lift, and almost all of it is in the direction of rotation, so there is little added drag. The prop is moving forward at the aircraft's speed in full feather, and to this speed, we must add the speed of rotation.

For you math buffs, by the following formula:

PropTipSpeed = Sqrt (Radius^2 X AngularVelocity^2 + TAS^2)

where:

Angular Velocity in radians per second

TAS in feet per second

Radius in feet PropTipSpeed will come out in feet per second

One prop I'm accustomed to is 15 feet in diameter (C-46), and is driven by a 2:1 reduction gearbox. Here are some of the numbers for the prop tip at an airplane TAS of 120 knots:

Engine RPM	Prop Tip TAS (knots)	Remarks
10	120	At 10 RPM, negligible additional speed at prop tip.
50	122	At 50, we pick up two knots at the tip
100	128	
200	148	
300	177	
400	211	
500	248	At 500 prop RPM (1,000 engine RPM), we've doubled the TAS at the tip
600	287	
700	327	
800	368	
900	409	
1000	451	
1100	493	
1200	535	
1350	599	At 1,350 prop RPM (2,700 engine RPM), the prop tip is moving five times faster than the airplane!

You will not see prop tips moving much faster than 600 knots, as this is getting too close to the speed of sound, and all sorts of nasty aerodynamic things start to happen in the vicinity of the prop tips. The noise alone is bad enough!

This, by the way, is the reason for using a reduction gearbox between the engine crankshaft and the propeller. Engines are most efficient when they turn fairly fast, while props do best when they turn fairly slowly. Direct-drive engines operate at a compromise between the two. Geared engines permit both the engine and prop to operate more efficiently, but with penalties in weight, complexity, cost, and sometimes TBO.

Windmilling

But back to our thought experiment, where we can control prop pitch directly. Remember, the engine is being turned by the prop, it is <u>not</u> yet developing any power, we've still got the mags and fuel turned off for this experiment. (This is <u>not</u> the correct way to restart an engine, we're just playing here!)

In the chart above, note that at a prop RPM of about 500 (engine 1,000), half the tip speed is coming from the forward speed of the airplane, and half is coming from the rotation of the prop. I don't know the blade angle, but in order to develop the "lift" to rotate the prop that fast, there must be a considerable angle. Just as a wing at a high angle of attack produces a drag component, the prop is now producing a "lift" component that is turning the prop, and a drag component that is acting to the rear, slowing the airplane. The normal range of movement of this prop is between 10 and 42 degrees blade angle, so you can see that if it's developing enough "lift" to windmill the prop and the engine that fast, it must be producing an awesome amount of drag on the airplane. It does!

Continuing our thought experiment one step further, let's assume we can set the blades to "totally flat." Without the engine running, the prop will slow down again, and come to a stop, this time pushing the blades through the air at 90 degrees. Draggier than when in feather, sure, but not anywhere near as much drag as when the prop blades were acting as airfoils.

From this, we can see that a windmilling prop is similar to an airplane gliding, without power. A stopped prop is similar to an airplane falling flat, with no forward speed. Which do you think will produce more "lift" and less vertical velocity?

This is why a windmilling prop has the highest performance penalty on the airplane, why a stopped prop is "better," and why a feathered prop is the best of all (if the engine isn't running).

With the 15-foot prop above, with the prop lever full forward (a bad thing), at 138 knots airplane TAS, this prop will windmill the engine at the full 2,700 RPM, with a prop tip speed of about 603 knots <u>without the engine running!</u> If we increase the airplane TAS, the governor will kick in (assuming there is oil pressure) and increase the blade pitch, maintaining the RPM at 2,700. If we decrease the TAS, the blades cannot move beyond the flattest pitch, and the RPM will drop.

In summary, the governor will do a fine job of maintaining the RPM set by the pilot, so long as other conditions do not place the prop blades on the mechanical limits. Once those limits are reached, the prop is essentially a fixed-pitch prop until conditions change and return the system to conditions of airspeed and power that will permit the governor to resume control.

Be careful up there!

June 14, 1999

Pelican's Perch #18: Mixture Magic

If you fly recips, what leaning procedure do you use? Chances are that almost everything your CFI told you about using the red knob — and most of what you've read and heard since then — is just plain hogwash! We suggest you forget everything you thought you knew about the subject, and let AVweb's John Deakin show you how to optimize engine efficiency and longevity through enlightened mixture management.

By John Deakin

Columnist

There are few things in airplanes as misunderstood and misused as the mixture control. Old Wives' Tales (OWTs) abound, many of them spread by POHs, the FAA, and even the engine manufacturers! Not much of what you've read and heard about mixture management makes sense — much of it is out of context, and most of the good stuff is so dry, dull and boring that it's tough to get through it without falling asleep.

I have flown with pilots who say, "Oh, I never lean, it's just too complicated, and fuel is cheaper than an engine overhaul, anyway." What really annoys me is that some of them even make TBO that way! What they don't think about is how many problems they have enroute to TBO — fouled plugs, burned valves, cracked cylinder heads, etc. — and how much money they waste on fuel. Even worse, they don't think about how much time they waste making unnecessary fuel stops. Yeah, yeah, I know, your bladder range is more limited than your fuel range. I've heard that before, but it sure sounds like a cop-out, to me.

Ever make an extra stop for "cheap fuel?" Do you feel smug when you buy fuel for ten cents a gallon less than usual? Why, then, do so many pilots fail to learn a little about their engines and save 20% or more on fuel used? That's just like getting forty cents off per gallon, these days! What am I missing here?

Others will tell me, "I lean to 50° F rich of peak, just like the POH says," not realizing that this can be — and often is — the very worst possible setting they can use!

Still others will decide on some arbitrary power setting with no particular logic in mind. 65% is a very common level. They'll carefully set the MP and RPM to the book values for 65% and figure that's all they have to do to attain that power setting. Wrong, it also takes a very careful mixture setting, as well!

Don't be afraid of that red knob. Learn to use it! With a few pretty obvious exceptions there is nothing you can do with the mixture control over a short period of time that will hurt you or the engine. Used properly, you'll save a lot of fuel, your engine will run cooler, cleaner, smoother, and longer, with less maintenance expense and downtime along the way to TBO.

There! Now that I've gotten all that off my chest, lets see if we can make a little sense of all this. If you haven't read my previous columns on manifold pressure and props, this would be a good time to do so, as this is the third in a series and builds on those earlier efforts.

I'd like to first discuss some things about the fuel we use, then go rather deeply into the operation of a "perfect" engine. After that, I'll offer a little history of why and how our engines are not perfect, and what we can do about it.

Pyromaniacal Prattling

If you've been to the movies, or watched TV in the last 30 years, you've undoubtedly seen the shot where someone pours a long trail of gasoline on the ground, then strikes a match and lights it off. If you watch closely enough, the flame is a fairly gentle one, and the flame front moves fairly slowly until it reaches whatever is going to explode, and then blows up — violently. A favorite shot is the car gas tank. While Hollywood plays tricks with physics now and then, this particular one doesn't need much fakery: it's quite real.

But why does the fuel burn so slowly as the fire snakes across the ground, and why does it blow up so violently when it reaches its intended destination? The short answer is "mixture."

By itself, gasoline won't even burn. Try dropping a lighted match on the tarmac and then pouring some liquid gasoline onto the flame: You'll put the fire out. This is the "too rich to burn" case.

Returning to that movie scene, the trail of gasoline across the ground only burns because the gas is evaporating, changing into a vapor, and at some point above the surface the mixture will support combustion. That little bit of vapor burns, lighting off the next few molecules, which light off the next batch, and so on.

If we could closely examine what's going on, the surface of the liquid fuel would not be burning at all, there would be a thin layer of very rich vapor just above it, also too rich to burn. At the point above the surface where combustion does take place, the fire burns "up," and all the combustible mixture above that point also burns. Blow a gentle breeze across this process ("fan the flames"), injecting more air into the process (leaning it out) and you'll see a much more vigorous flame, and a much faster flame front. Blow even more air, and there will be too much air (too lean), and the fire will slow down again, and ultimately go out.

Now, what happens when the burning trail of gasoline reaches its destination? If the fire hits a full gas tank, the fire will simply go out! The liquid is again too rich to burn. But if the tank is partially empty, there will be a nice volume of combustible gasoline vapor at just the right mixture in the upper part of the tank. The smallest spark is more than enough to light that off, and the flame front will expand rapidly in all directions. The rapidly expanding gasses will blow up the tank, scattering the liquid fuel, nicely mixing it with air, and creating an even larger volume of highly combustible fuel/air mixture. Technically, this is not an explosion: It's still just burning. But it takes place so quickly that it appears to explode.

Another example. Propane (or acetylene, or any flammable gas), right out of the tank, makes a rather lazy, sooty yellow flame that really isn't very hot, only a few hundred degrees. Add air to that mix, push it out that pipe under some pressure, and it turns into a hissing blue jet of flame at several thousand degrees. Your gas stove is cleverly designed so that the rising heat sucks air into the gas stream, making a mixture that burns with a nice hot blue flame. But mix too much air with that gas, and the flame becomes weaker, weaker, and finally dies out — the fire is burning so slowly it simply can't leap from molecule to molecule. Well, at least that's the way I like to think of it!

All this is a very good thing, because if any of these substances could burn on their own, the fire would run right back down the supply line to the tank, and burn it all — quickly!

It's All in the Mixture

How does this translate into the gasoline-powered, spark-fired, internal combustion engines found in our airplanes (and also in tractors, lawn mowers, and cars)? For purposes of this article, I'll limit my discussion to normally-aspirated engines, leaving turbocharged ones for a future column.

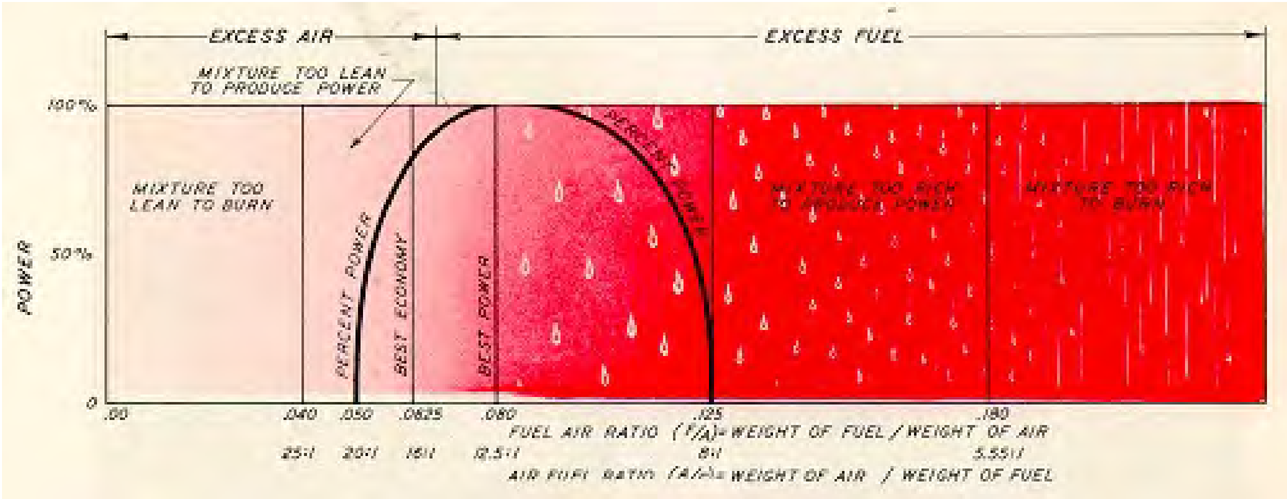
In the engine that powers my Bonanza (a TCM IO-550), if I flip the boost pump to high with the mixture rich, I can literally "flood" the engine and kill it at a low power setting. Any malfunction that pumps "too much" fuel into the combustion chamber (relative to the air) will do the same thing. The fuel is flowing, the spark is sparking, and the airspeed is still turning the prop, but there's just too much fuel and not enough air. Flip the boost to "Low" or "Off" or lean it out with the mixture control and the engine will run again. Given the correct fuel flow, air flow and spark, it must start and run.

An aside here. Two people report that when they have run a tank dry as I described in another column, they have had a minor problem re-starting. This may be a possible explanation if they shoved the mixture in and flipped the boost pump on at high altitude. The engine goes quickly from "no fuel" to "too rich to run" and can't start. If you run into this problem, don't change anything but the fuel selector, and maybe flip the boost on momentarily, just to get the fuel started again to the engine-driven pump, then turn it off again. That engine will start. After all, it is FAA-certified to do so!

At the other end of the spectrum, pulling the big red knob all the way back cuts off all fuel to the engine, making the mixture "too lean" and also causing the engine to quit. We do this to shut down the engine on most airplanes, so this is more familiar territory to most.

Fire in the Hole!

Somewhere in between those two extremes of "too rich to run" and "too lean to run," there is a small range of mixture settings that will allow the engine to run. At each end of that small range, the engine doesn't really run very well, but things get better in the middle of the range. It is this range of "burnable" mixture we need to understand. So, read on.



(This picture, and several others in this column comes from the superb Pratt & Whitney "The Aircraft Engine and its Operation", February 1955 edition. I have arranged to have this publication duplicated, in color. See www.flybyeknightpress.com

The chart above depicts only the lower end of the mixture range, from "no fuel" to about 20% fuel, by weight. Obviously, any mixture greater than 20% fuel is also "too rich to burn."

Note also that only a very narrow part of this will actually support combustion at all, from roughly 5% to about 12.5%. Remember we're talking here about <u>weight</u> of both air and fuel. At 20:1 by weight, the mix is 20 <u>pounds</u> of air, and 1 <u>pound</u> of fuel. By volume, that's about 2,000 gallons of air for each gallon of fuel.

Let's do a little thought experiment here. Assume you are in cruise at 10,000 feet, with wide-open throttle and the prop control set to 2,300 RPM. Now cut the mixture, shutting the engine down. The prop governor will attempt to maintain that 2,300 RPM, and for the purposes of this exercise, let's assume it can, and does. Thus, even with the fuel cut off, the engine is still turning, the pistons are still pumping air, and you'll still have the same manifold pressure (about 20 inches). All engine instruments will remain normal, except CHT and EGT which will drop pretty quickly. You establish a nice power-off descent with enough speed to keep the prop windmilling within the governing range. (This is a learning exercise, and <u>not</u> an engine-out drill, where you'd reduce to "best glide.")

For most normally-aspirated engines, as you get down around 8,000 or 9,000 msl, the resulting manifold pressure and RPM will be <u>approximately</u> correct for the classic 65% power setting. How much power are we getting? <u>None</u>, of course, or 0%. My point is that MP and RPM alone do not determine power output. Obviously, mixture plays a major part in the power equation, too!

Continuing our thought experiment, you're at the extreme left end of this chart, all air and no fuel ("too lean to burn"). Now, start easing the mixture control in (moving to the right on the chart). At some point, that will begin to allow fuel into the air, but still, nothing happens until that "mix" gets to the 5% point. At about that point, the engine will start rather abruptly. If you look closely at that chart, the power curve rises just about vertically to around 30% of power, and only a tiny bit more fuel will bring it to 50% power. After that, it takes larger and larger increases in fuel to get to 100% of available power. Note there's a fairly wide "flat spot" on top of that curve, where power stays pretty constant. Note also that if you enrich even further, power drops off again — ultimately, to zero ("flooded out").

Adjusting the mixture level (by weight) to about 8% fuel will get the absolute maximum horsepower out of that fuel and air mixture, so we call that "Best Power Mixture." No matter how you play with the mixture, that's the best you can do for sheer, raw power. This setting is useful for maximum speed, maximum climb, and for converting gas into noise. This is "Maximum Power for the Fuel and Air available."

Most of the cruise performance charts in General Aviation aircraft POHs either don't mention it all, or there is a tiny note somewhere that the chart numbers are valid <u>only</u> with a mixture setting at "Best Power" (at the top of our power/mixture curve). This is often a marketing ploy, as faster airplanes sell better.

Now here's a slippery concept for many (well, at least I had trouble with it). If we re-lean the mixture a bit, say 10% (moving back to the left on the chart), the power doesn't drop very much, perhaps only 5%. Hmm, think about that. 10% less fuel, 5% less power. This seems more efficient — and it is. We're not getting the maximum horsepower, we're getting a <u>little</u> less, but for a <u>lot</u> less fuel. (There are many things in aviation that work this way. Give a little here, get a lot there.) Tests have shown that at about 6.25% of fuel (by weight) we won't get as much power (it'll be roughly 80%), but we will get the most power per gallon, and we call this "Best Economy".

To look at it another way, by running at "Best Power," we are wasting a little fuel to increase the power.

In this context, when we speak of "power," we're speaking of the power available from a particular amount of air and fuel, and <u>not</u> some percentage of "rated power" from the engine. In other words, this mixture diagram applies whether we have half throttle and 1500 RPM, or any other setting. For <u>any</u> given setting of throttle and manifold pressure, this chart of combustible mixtures applies.

In fact, sitting on the ground, idling at 1,000 RPM, you can see this. The prop is well out of the governing range and at its flattest pitch. RPM is thus a direct indication of power. Full rich, flip the boost pump on, and you may flood the engine out completely. But quickly pull the mixture knob back to keep it running. With this setup, you can vary the mixture, and watch the results on the tachometer. Too rich, the RPM will be low, the exhaust will be sooty. Lean it, and you'll come to an RPM peak. Keep leaning further and the RPM will drop again — eventually to zero. It gets very sensitive at the extremes, because of the steep slope of the curve on the combustion chart.

The mixture control is the most important "power control" we have! Using the mixture alone, we can vary the power from zero (lean) to "full," and back to zero (rich). We can't do that with the throttle (there's always some power at idle) or with RPM (unless we can feather the engine.) Of course, for practical purposes, the real range of power control through mixture adjustment is from about 30% on the lean side, to 110%, and back to 30% on the rich side.

Interpreting the Gauges

For far too long, these engines have been run with no science at all. We simply haven't had any decent instrumentation to tell us what's going on in the combustion chamber. If you've read my previous columns on manifold pressure (MP) and props (RPM), you now realize that neither MP nor RPM is a very good indicator of power or what's happening inside the engine. The story they tell is incomplete, because it ignores the profound effects of mixture.

If your airplane has the old-style Cylinder Head Temperature (CHT) instrument, it probably has a green arc (or line) to denote normal operating range, with a redline at the upper end, and maybe even no numeric temperature markings at all. The CHT probe is often not even on the hottest cylinder, or in a location that will yield useful information. The early single-probe Exhaust Gas Temperature (EGT) systems were little more than a good thought, because some only measured the EGT in a single cylinder, or an average of half the cylinders, or maybe an average of all the cylinders (depending on the probe location). What few realized is that because of a severe mixture maldistribution, these engines are nothing more than a collection of four or six separate one-cylinder engines, flying along in loose formation. A single EGT indication from one of them — or even an average of all of them — is virtually meaningless, because the others are certainly doing something very different from the one you're watching.

In the big old radials, where we can often watch the exhaust at night, we can see directly what is happening. At full rich (takeoff and climb), the exhaust is a bright yellow, with visible flames licking (slowly, relatively speaking) back along the cowling. Lean it out, and the flame turns blue, becomes shorter, and burns more intensely (quicker). Keep on leaning, and it turns white with a noticeable loss in power. If you lean it far enough, the fire goes out and the engine quits. In the early days of the big radials, it was easy enough to learn how to lean the engine by sight at night, develop a "feel," and duplicate it closely enough in the daytime. The design of the big radials also allowed a direct measurement of actual power being delivered to the prop, and this led to some very scientific leaning methods indeed, based on actual power. This "art" had become a real science towards the end of the heyday of the big radials — on DC-7s, Connies, and others — both in the airline world and in the military. By any accounting, there were several hundred million hours of accumulated experience on large fleets, under highly controlled and monitored conditions, by professional crews who had to operate in a very consistent and standard way, using some pretty sophisticated tools for those times.

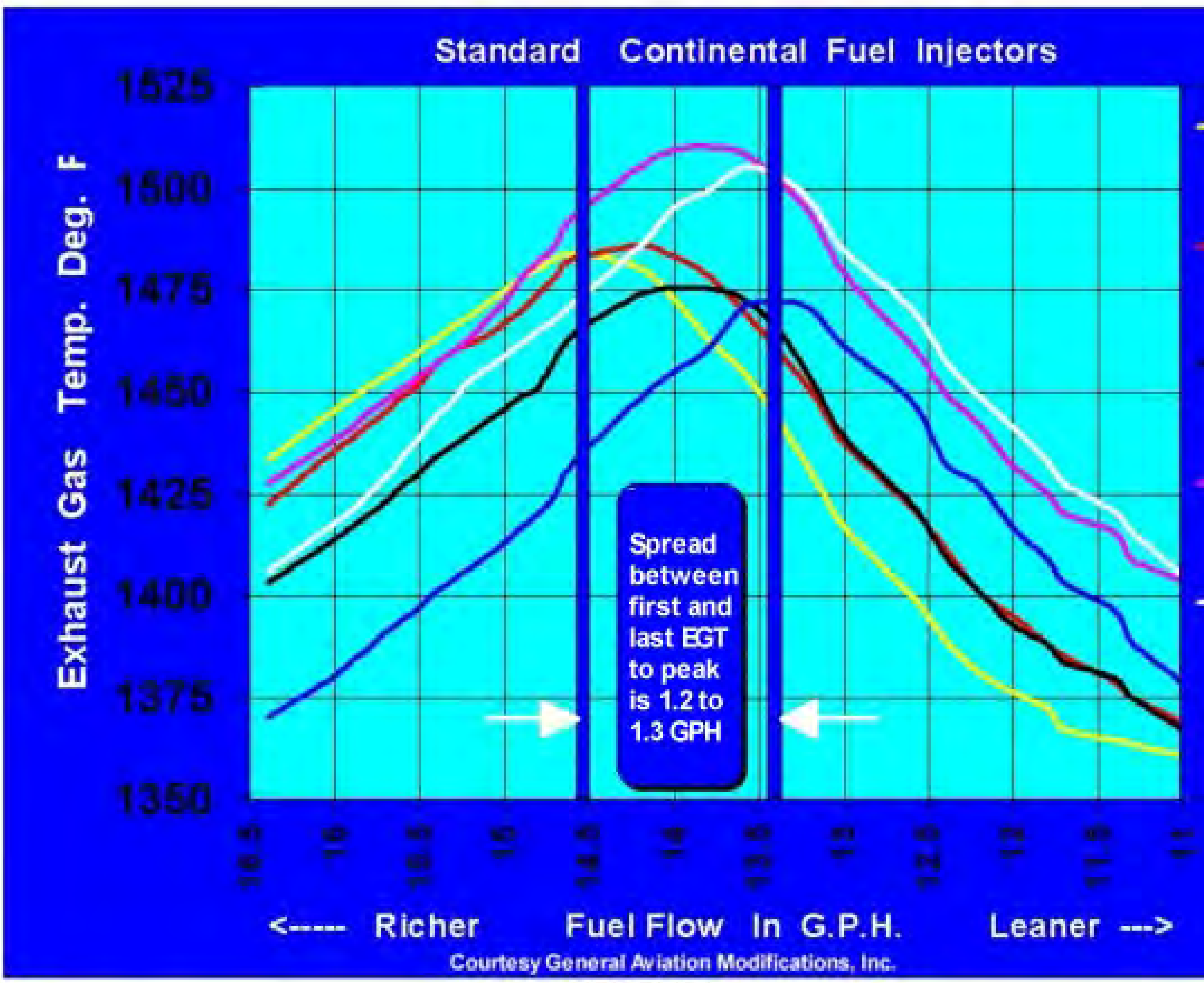
Another wonderful feature of the radial engine is that the intake pipes are all the same size and shape, and they radiate from a central point. This gives a wonderfully even air distribution to all cylinders. In many of the radials, there is also a gear-driven supercharger at that central point, which is just a centrifugal impeller. The fuel is often sprayed into the airflow just before it gets to that impeller, resulting in a nice, even mixture. As a result, not only is the air distribution very good, but so is the fuel distribution.

(Research by Walter Atkinson since this column was written has turned up data somewhat contrary to the above, the mixture is not as even as we thought! By the judicious use of carburetor heat, the mixture distribution can be improved dramatically. In retrospect, many of the old manuals for these big radials did recommend carb heat control as part of the cruise procedures!)

We lost all that with the "flat fours" and "flat sixes" that power most GA aircraft today. There is no practical way of measuring power directly, the exhaust cannot normally be observed from the cockpit, and the mixture distribution is often dreadful as the engine is delivered from the factory. Intake pipes of the "log runner" type are of dramatically different lengths for different cylinders. Despite this, the actual air distribution is pretty good in the big-bore TCM engines. Most Lycoming engines, however, have a "plenum" type induction system that provides somewhat unbalanced air distribution that changes with engine RPM.

Still, many of these engines have terrible fuel distribution. The carbureted engines are the worst *(absent carb heat, above)*, but many fuel injected engines are not a lot better. (Fuel injection does have other benefits, however.) Again, what we really have is six (or four) cylinders flying along in loose formation, each doing their own thing with regard to mixture, while the pilot has only one mixture control, a "master mixture" if you will, which simply controls total fuel flow to all of them.

Here's what that looks like in a typical TCM IO-520 or 550, with stock injectors, and all cylinders instrumented. Some engines are "better," others are "worse."

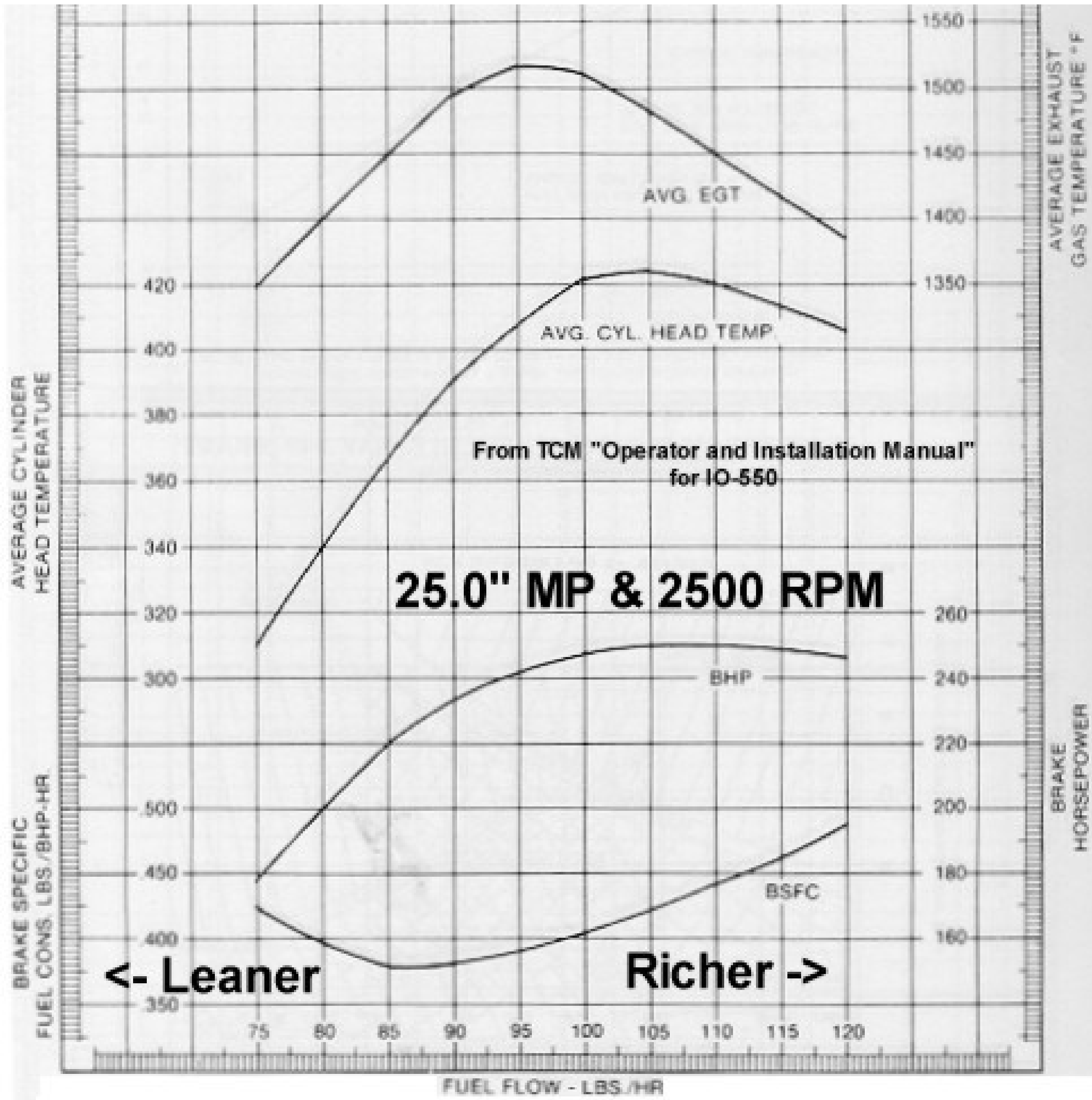


For simplicity, this chart shows only the six EGTs plotted against fuel flow. In this chart (unlike the previous P&W chart), "richer" is to the <u>left</u>, "leaner" to the <u>right</u>. If you start with "full rich" on the left side, and lean slowly, you will see all EGTs rise together at first. At about 14.5 GPH, the #1cylinder peaks, and then starts cooling off on the lean side of peak. Very shortly thereafter, #2 does the same. (#1 and #2 are the rearmost cylinders in the big-bore TCM engines.) We continue leaning, and soon #3 and #4 (the middle cylinders) hit peak EGT and start down, while #5 and #6 continue rising. Finally, at about 13.3 GPH, the last cylinder peaks. But what has happened to number 1, the first cylinder to peak? It is now 40 degrees lean of peak (LOP)!

Understanding the Relationships

That relationship between "Best Power" and "Best Economy" is but one aspect of this subject. What is happening to the EGT while we lean? What is happening to the CHT? What is happening to the fuel consumption, and the power? More importantly, what is their relationship to each other?

TCM, like Pratt & Whitney and Wright before them, publishes a neat little chart showing this. Some are surprised that the charts from these different engine manufacturers all look just like each other! When you think about it, this is not really that strange, because the principles are the same, the metallurgy is the same, the sparks occur at about the same time and the geometry of the pistons, rods, and crankshafts are the same, whether the engine is from a DC-7, a Bonanza, or a John Deere tractor. Here's one such "relationship chart" from TCM:



Now, please stop right here. DO NOT just skip over that chart, it's important. It looks a little complicated, because there are four parameters on one chart, and each needs to be understood. If you are not prepared to understand that chart, I don't think you can understand how to operate your engine properly, much less understand the rest of this column. Please take the time, right now, to follow me through on this chart!

The entire chart represents data while running at 25.0 inches of manifold pressure and 2,500 RPM. Those are held constant — only the mixture changes.

Please read the preceding paragraph again, it's VERY important.

The only variable is the fuel flow, plotted across the bottom of the chart, and all four parameters are plotted against that fuel flow from 75 to 120 pounds per hour (PPH). This gives a lovely picture of the relationships. Note that "Richer" is again to the right on this chart (I could have swapped some of these charts left to right to make them all the same, but preferred to stick to "authentic.")

The right side of the chart is not necessarily "Full Rich". For whatever reasons, TCM chose to show just the range of fuel flows from 75 to 120 PPH on this IO-550, while "full rich" at sea level is about 162 PPH

The top curve shows EGT, aligned with the numbers on the right side, from a low of 1,350° at 75 PPH (lean), peaking at about 1,520° F at 95 PPH, and dropping again to 1,380° F at 120 PPH (rich). This is a classic EGT curve, and many of you will be familiar with it. There, now that's not so bad, is it? And you thought this chart was too complicated!

Below that is the CHT curve, with the scale at the left. About 310° F at 75 PPH (lean), peaking at about 425° F at 105 PPH, dropping again to about 405° F at 120 PPH (rich). Note the CHT peaks at a substantially richer mixture than EGT. (In fact, you'll see that the hottest CHT occurs at the point where EGT is about 50° F rich of peak (ROP). Hmmm, where have we heard that before?)

The third trace from the top is "brake horsepower" (BHP), which we can just call "Power" as delivered to the shaft. The numbers for this trace are on the right, and our trace shows 180 HP at 75 PPH (lean), peak at about 250 HP for fairly broad range of fuel flows, and drops only slightly to about 245 HP at 120 PPH (rich). Note that going all the way to "Full Rich" would produce a good deal more fuel flow and a good deal less power.

Finally, the bottom curve depicts "Brake Specific Fuel Consumption" (BSFC). This fancy-sounding engineering term is nothing more than the fuel required to produce one horsepower (HP) for one hour.

A useful trick to help you understand this chart is to lay a clear plastic ruler vertically on the chart. Keeping it vertically oriented, move it back and forth horizontally. As one end of the ruler moves over the fuel flow scale at the bottom of the page, the four curves will move up and down along the ruler's straightedge, just as those parameters move up and down in the real world.

Remember earlier, where I said we could lean a lot and only lose a little power? Well, this curve gives us a visual idea of how that works. At 75 PPH (lean), it takes about 0.425 pounds to produce one HP for one hour. In the range 85 to 95 PPH, less fuel is required: about 0.385 pounds of fuel. Enrich further to 120 PPH, and you'll be burning about 0.480 pounds of fuel to produce one HP for one hour. In this case, "less is better" if we're looking for economy. BSFC is a very useful term, as it is a direct indication of an engine's efficiency. Modern automobile engines, contrary to popular belief, are not very efficient, having BSFCs above 0.42 or so. They are designed to run very clean, however, and sacrifice some efficiency as a result. TCM engines can achieve BSFCs as low as 0.385 from the factory. With modifications, we're going to do better than that. Not too shabby for "World War II technology," as so many call it!

Now, here's the crucial concept behind this chart: All four curves are carefully plotted with reference to the fuel flow scale at the bottom, and this gives us a lovely opportunity to look at the relationships between them! If you'd like to know what is happening to CHT as you fiddle with EGT, the answer is here.

For example, let's say we've leveled off in cruise, allowed things to settle down and it's time to lean, at whatever MP and RPM you choose. Starting from full rich (perhaps well off the right side of this chart and due to the enrichment feature at full throttle), we start leaning. According to the chart, the EGT and CHT will rise, and we know this to be true from experience. The power rises only slightly. If you're going for absolute maximum altitude or speed, that very flat "peak" in the BHP curve that occurs around 105 to 110 PPH fuel flow will be helpful, and if you're making a high-altitude takeoff, it will be very helpful. The BSFC is dropping as you lean, of course, you're getting "more efficient."

So as the mixture is leaned, power peaks first, with CHT peaking at very close to the same point. In practical terms, if we lean to max CHT, we'll have max power for that MP/RPM setting. Doesn't that make sense, intuitively? Max power, max CHT? It's not precisely true, but it's close enough.

Ok, so power peaks first, stays pretty flat, and then CHT peaks shortly thereafter. With continued leaning, power and CHT drop together — very gradually at first, then progressively more steeply — while BSFC continues to improve and EGT continues to rise.

Continue leaning, and EGT peaks and begins to fall, while BSFC continues to improve. Sure, we're losing power, but fuel consumption is declining even faster, so our "economy" (as measured by BSFC) is still getting better.

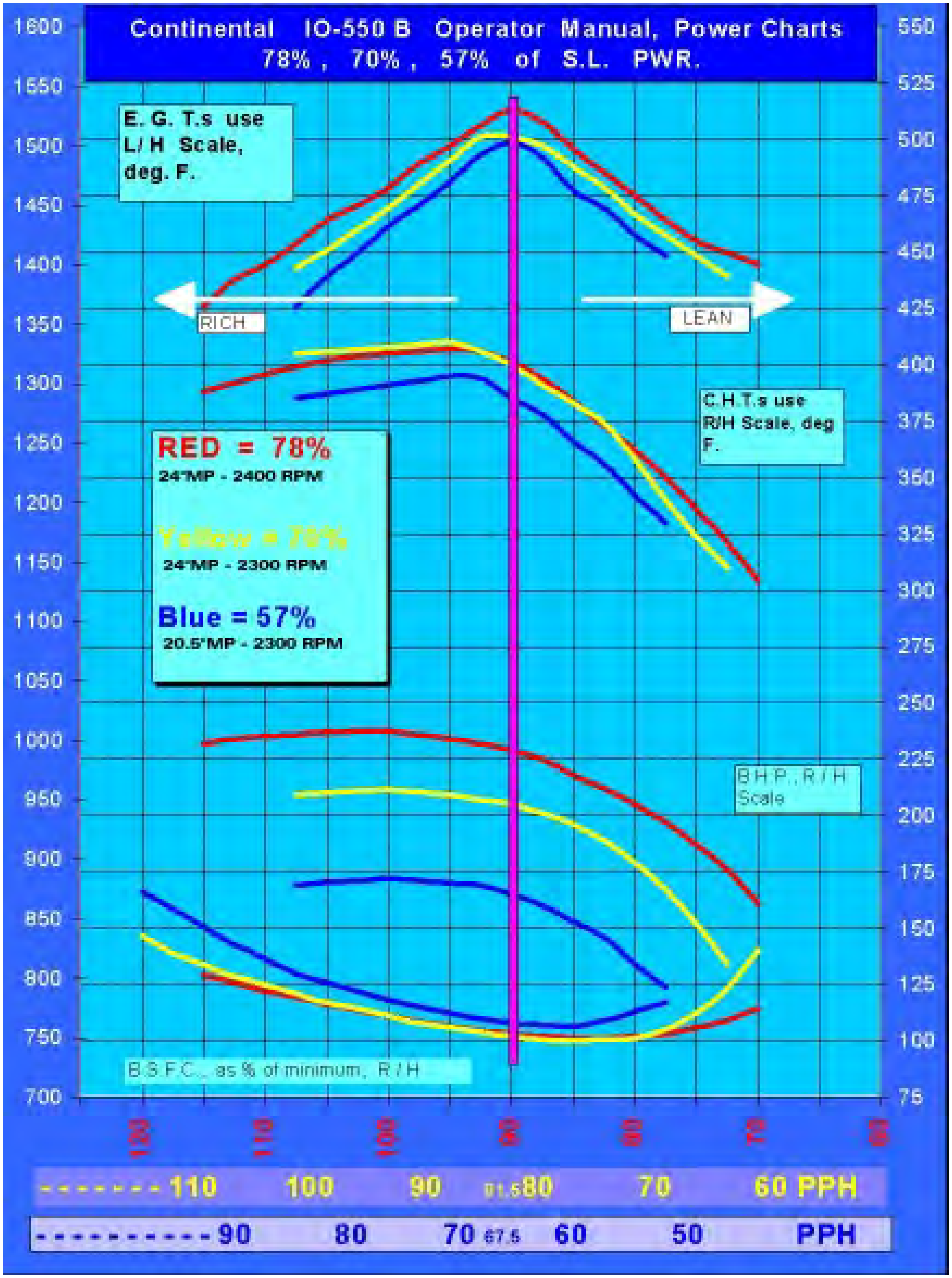
Finally, BSFC bottoms out (at "best economy mixture"), and stays pretty flat between 85 and 90 PPH. If we disregard the small difference between 0.385 and 0.400, we could even stretch the point a little, and say the BFSC curve is "kinda flat" between 85 and 100 PPH. Look immediately above at the HP curve, and note that for a small loss of fuel efficiency, we can pick up 25 to 30 HP? Isn't that interesting? We'll see later how that affects airplane performance and efficiency, a very different subject. But to make a long story short, if the power setting that results from optimizing engine efficiency causes your airplane drop below the airspeed range that provides optimum aerodynamic efficiency, you're not gaining anything! That's a whole 'nother can o' worms. (I feel another column coming on.)

But What If We Change MP or RPM?

Let's say we have carefully set up a real 65% of rated power, using the required MP/RPM, with the mixture leaned to Best Power.

What would happen to this if we increased the MP and/or RPM, keeping the mixture constant at Best Power? More power to the shaft, right? Think about what this might do to that chart. Since the power moves up, all the curves must move up. Since the peak EGT will occur at a higher fuel flow, it must move to the right, and all the other traces will move right, too, to preserve the interrelationships.

Here's what that looks like:



Note the left-right relationships don't change on this chart, because we've fiddled the fuel flow scale at the bottom to keep them aligned.

Heads up, crucial concept coming! Assume that we increase MP to increase power output to something substantially above 65% power. Now suppose we lean the mixture a bit, until the actual power drops to exactly 65% power again?

Here's exactly what that looks like:

This is a real picture of a Cessna 414, previously trimmed up very carefully for straight and level flight at equal MP, RPM, and mixture settings. After that, the throttle is increased, and the mixture decreased, to produce what you see here, with no tendency to yaw/roll/turn. This situation is actually very sensitive to very small differences in power.

Remember,both engines are producing exactly the same power!

The left MP is 3" higher than the right, but the left fuel flow is 3.2 GPH lower! Note further, the EGT is only 10° F higher, but the CHT (as shown by the missing bars on the Graphic Engine Monitor display) are 1 to 3 bars lower, with each bar representing 25° F.

Ponder this: cooler CHTs, less fuel, same power. Sounds like magic, doesn't it? Why, if we could run that MP up high enough, and pull the mixture back far enough, we might invent perpetual motion! Unfortunately, this is another aviation case where a little is good, but "more" isn't. There are other forces at work.

Geometry and Physics into the Fray

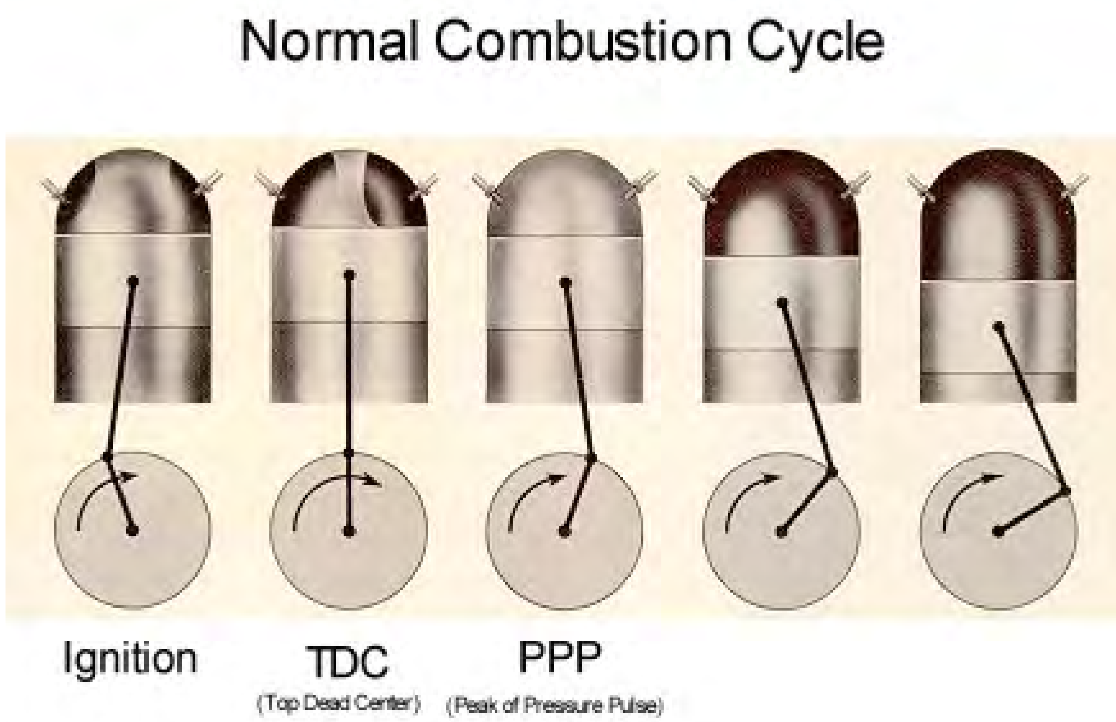
Just as there is a right time to make your move on that blonde across the room, there is a right time to "light the fire" in the cylinder. (In my experience, the latter is far more easily determined than the former.) Intuitively, you would think it a simple matter, just light it off when the piston hits TDC (Top Dead Center). But the fact is, it takes quite a bit of time to light that fire, and for the flame front to propagate sufficiently to do anything useful. The fuel/air mixture nearest the spark plug must be in the combustible range, and the fuel molecules must be close enough together to continue the process. Even under the best of circumstances, combustion is still something of a random process, so there is a variation from cycle to cycle in the same cylinder. But for the most part, the molecules cooperate with great glee, flinging themselves into the fire in order to do useful work, even if that's only to transport us to the site of a $100 hamburger.

The best time to "light the fire" also changes with RPM and mixture. At a high RPM, it takes a short amount of time for the piston to rise and fall. At a slower RPM, it takes longer. But the flame doesn't know anything about pistons rising and falling (or crankshafts turning), it's still burning at the same speed. (Well, almost.) This can change the point at which useful work is done quite dramatically. When, then, should we "light the fire?"

The answer depends on all three engine parameters — mixture, RPM and MP — so ideally our ignition timing would be adjusted accordingly. Some of the big radials do in fact have variable spark settings, but the flat engines most of us fly behind are stuck with fixed timing. (But "Stand by for NEWS!") Since maximum power is the most critical case, ignition timing is typically set to be “acceptable” at full takeoff power, and operation at lower power settings is something of a compromise.

At maximum power, long experience has shown that discharging the spark at 20° to 25° before top dead center (TDC) is about right. That much “lead time" gives the fuel/air charge time enough to develop a good fire, and the pressure will start to build just as the piston reaches the top-of-stroke. From that point, the fire gets really serious, and the pressure builds rapidly, just as the piston starts falling away.

Again, through long experience and actual measurement, it is clear that about 16° to 18° after TDC is the best place for that pressure peak to occur, in order to extract the maximum amount of useful work, as shown by the following picture from the Pratt & Whitney book:



As you can see in the first picture, when ignition occurs the crankshaft knuckle is reaching the top of its arc, which also puts the piston very close to the top of its stroke. At first glance, igniting the charge at 22° before TDC seems like it would be counterproductive, since the piston is still coming up. However, in reality, it takes some time for the fire to get going, and by the time that happens, the piston is already pretty much topped out, so the building pressure cannot really produce the "negative power" you might have expected at this point.

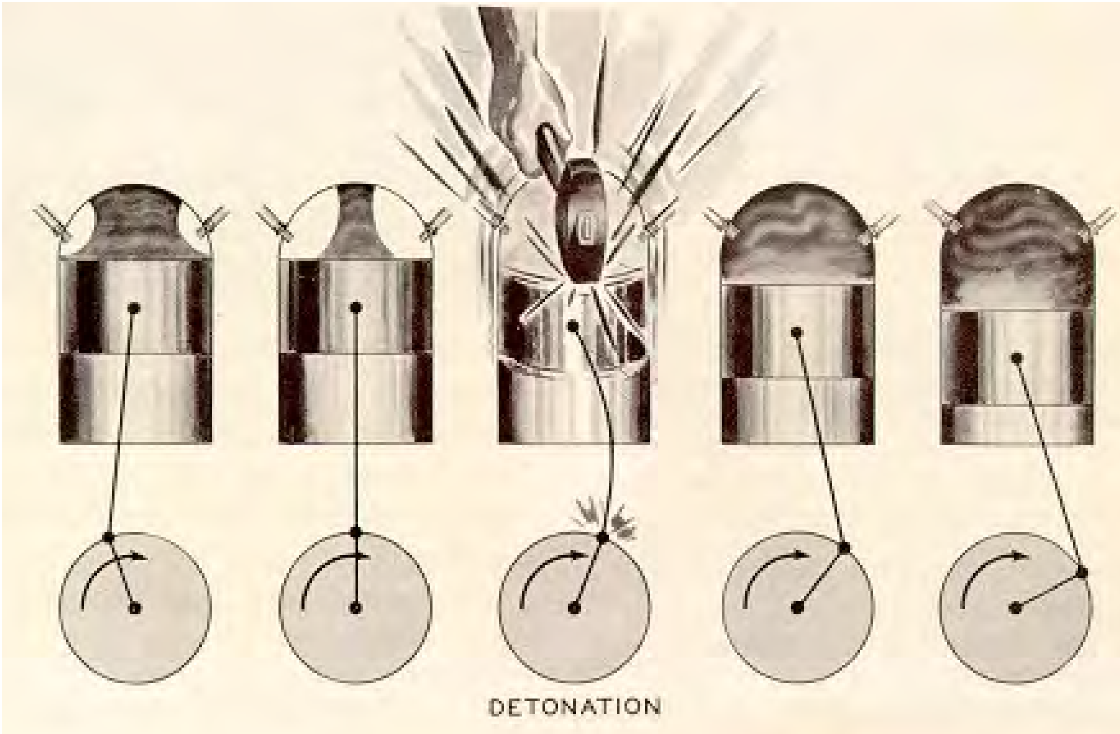
The second picture shows perfect TDC. No matter what the pressure in the combustion chamber is doing, there is no "mechanical advantage", no leverage, as the piston is just pushing straight down on the connecting rod, which is pushing straight down on the crankshaft throw. Combustion chamber pressure at this point produces no useful work at all (but it sure loads the bearings.)

The third picture shows the approximate position of the assembly at the peak pressure point (PPP). If the pressure peaked a little sooner the piston would be at the top of its travel, with less mechanical advantage on the crankshaft, and engine stresses would get very, very high. At about 16° after TDC, some decent mechanical advantage is just beginning to take place, and that allows time for the rest of the combustion event to "push" the piston down. If the peak of the pressure pulse occurs much later than 16° , the initial peak would have a greater mechanical advantage, but then much of the energy in the later stages of the combustion event would be lost. On balance, a PPP at 16° after TDC turns out to be about the best you can do. Another compromise.

At very high power settings (such as takeoff power), we've found that throwing extra fuel into the mixture slows the combustion event, causing the PPP to occur later, helping keep temperatures down and thus allows us to develop even more power without the risk of detonation. This is why many engines have a "power enrichment" feature at full throttle. We're willing to waste some fuel for a worthy cause during takeoff, especially since we usually don't run at that high power for long. What would happen if we got all the way up to this very high power, and then pulled the RPM back? (Don't try this at home, folks!) Well, with the spark occurring at 22° <u>before</u> TDC and PPP occurring at 16° <u>after</u> TDC at full RPM, there is a very precise time interval between spark and PPP. The crankshaft rotation is 38° (22° + 16°). If we reduce the RPM by 20%, the crankshaft will turn only 30° (80% of 38°) by the time PPP occurs, so now the peak pressure will occur at only 8° past TDC.

The preceding analysis is actually a bit of an oversimplification. In reality, there are other factors at work such as the rate of compression at the slower crank speed, so the relationship between RPM and PPP timing isn't really linear. In this case, the PPP would probably occur more like 12° after TDC.

In any case, at maximum MP and reduced RPM, the peak pressure will be <u>much</u> higher, because the combustion chamber will be <u>much</u> smaller when PPP occurs. Since the pressure will be much higher, the temperature will be much higher, and this increases the risk of detonation. More on this later, but here's the same picture, this time illustrating classic detonation:



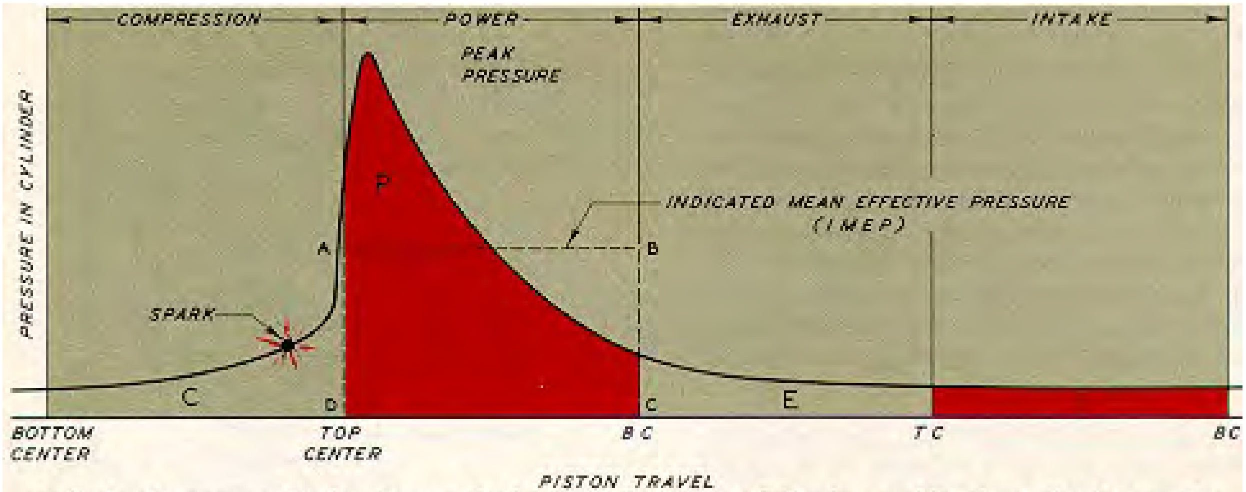
This is the reason for the old rule of thumb, "Always reduce manifold pressure before reducing RPM, and increase RPM before increasing manifold pressure."

This is not a bad rule, and it never hurts to do it this way. But you should understand that it really only applies in the high-power case where the engine is operating at maximum combustion pressures and temperatures, and detonation is therefore a possibility! If you're cruising at 22" and 2,100, and want to increase to 24" and 2,400, it doesn't really matter which control you adjust first, you won't hurt a thing. Sure, as a matter of habit, run the RPM up, then do the MP. But the engine isn't going to blow up if you do it the "wrong" way.

What about mixture at very high power settings? Remember, the engine manufacturer has optimized everything to produce all that power, and many parameters will be running within very narrow tolerances. Remember also the opening of this column, where I mention how much difference mixture makes in the speed of combustion. At takeoff power, if we bring the mixture control back a bit from full rich, the rate of combustion speeds up, and puts that pressure pulse closer to TDC. Again, a very bad thing. (Combustion speed reaches maximum around 50° F to 75° F rich of peak EGT, and further leaning causes it to slow down again.)

Our POHs instruct us to use full-rich for takeoff. The extraordinarily rich mixture is required to assure that detonation does not occur. The conventional wisdom is that the purpose of the "excess" fuel is to cool the engine, but in fact its primary purpose is to slow the combustion rate and delay the PPP, which eliminates the risk of detonation by reducing the pressure peak. This does, in fact, result in cooler operation, but that's actually a second-order effect of the delayed PPP. (If we could just delay the ignition timing for takeoff, we wouldn't need to throw all that extra fuel at the problem.)

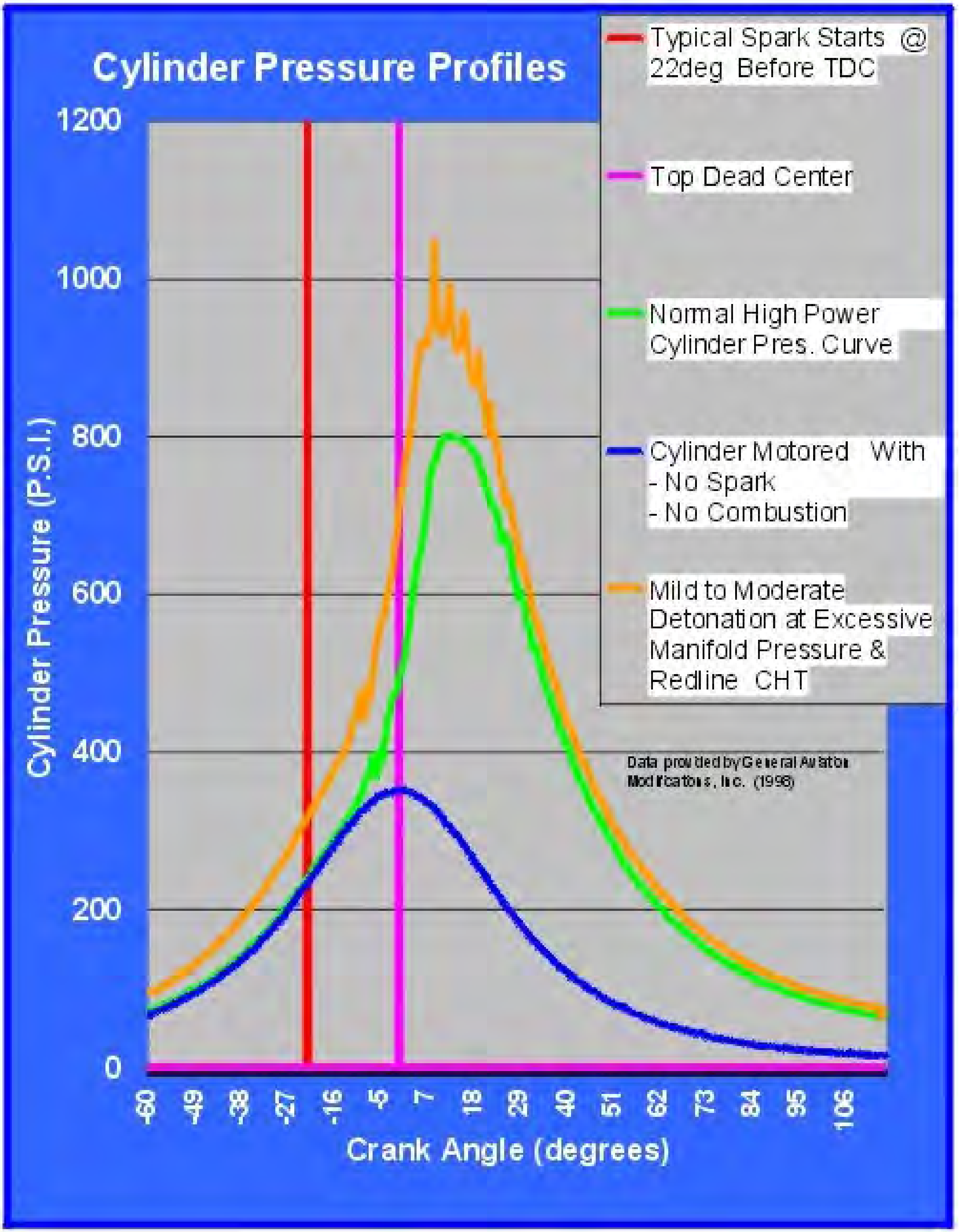
Here's what Pratt & Whitney thought a combustion event looked like, back in 1948:



Cylinder Pressures During Power Cycle (P&W "The Aircraft Engine and its Operation" page 52

Note how the pressure rises gradually to the point at which the spark occurs. It then rises very rapidly as the piston comes up to TDC, and continues to rise thereafter, mostly because the piston hasn't dropped very far, due to the geometry of the piston rod and crankshaft throw. Wouldn't it be lovely if we could keep that same pressure on the piston, all the way down? We can wish, can't we?

I don't know how Pratt & Whitney got that picture, but it's certainly pretty good, because here's the real picture, as measured by the latest state-of-the-art digital instrumentation at General Aviation Modifications, Inc. (GAMI) in Ada, Oklahoma:


Cylinder Pressure Profiles
Typical Spark Starts @ 22deg Before TDC
Top Dead Center
Normal High Power Cylinder Pres. Curve
Cylinder Motored With
- No Spark
- No Combustion
Mild to Moderate Detonation at Excessive Manifold Pressure & Redline CHT
Data provided by General Aviation Modifications, Inc. (1998)
Cylinder Pressure (P.S.I.)
1200
1000
800
600
400
200
0
-60
-49
-38
-27
-16
-5
7
18
29
40
51
62
73
84
95
106
Crank Angle (degrees)

The lowermost (blue) line is the result of simply spinning the engine at 2,700 RPM with no combustion going on at all. As you might expect, the pressure rises and falls directly with the piston travel, reaching a maximum at TDC. It is perfectly symmetrical on both sides of TDC, and rises only to about 350 PSI at TDC.

The next line up (green) is a normal combustion event. Notice the pressure rises almost identically with the blue line, even after the spark, until the point at which the rise in the blue line starts to level off. It is at this point that the "fire" has truly lit off, and begins to increase the pressure on its own. This one peaks at about 18° after TDC (the "PPP" or "Peak Pressure Pulse") at about 800 PSI, after which the pressure drops off gradually, but still producing a lot of downwards force on the piston.

Finally, the yellow line shows what detonation looks like. This is an abnormal condition. Note this is "mild detonation," not really "the real thing" that can literally reduce an engine to an expensive pile of junk in a matter of seconds. It was deliberately induced by redline CHT and excessive MP (from a turbocharger). Note very carefully how early this builds and peaks, relative to a normal event. The actual raw data shows it occurring at about 8° after TDC, and the test engine did not sound like a happy camper! I've heard it, and it was ugly!

Looking Inside The Cylinder

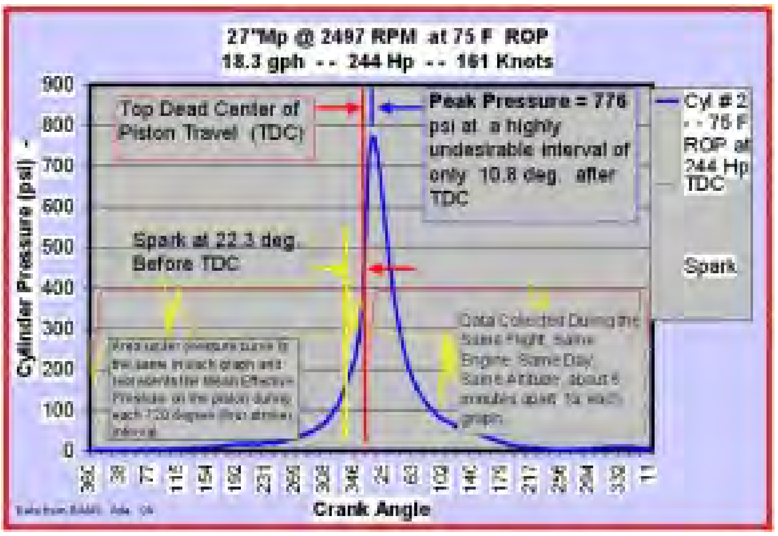
You need to understand a little about how GAMI gathers this data to appreciate the quality of what you're seeing. They use in-house proprietary software, hardware, and test equipment to gather this data in ways that have never been done before.

Driven by George Braly (rumors of whips and chains and piteous cries late in the night from converted tornado shelters abound) GAMI has developed a portable 128-channel data acquisition system that can be installed and operated in a Bonanza. It is entirely independent, with its own power source. Data can be captured to a laptop computer's hard disk for later processing, and can also be displayed in real time, up to 50,000 samples per second (all channels). Using specially-modified sensors, GAMI can capture real time data from the ignition system, crankshaft angle, fuel flow, a large array of temperatures (including several points around an individual cylinder), and anything else that can be sensed.

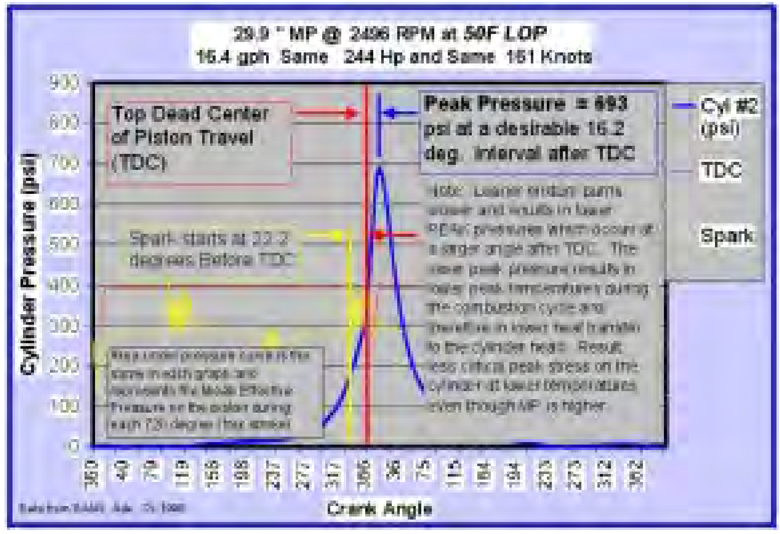
Most amazing of all to me is that this system can record actual instantaneous pressures within the combustion chamber at those same data rates! GAMI accomplishes this little trick by drilling a tiny hole down inside the barrel of the spark plug, and inserting a proprietary sensor that can measure pressure very accurately and at very high sample rates, sufficient to record every detail of the combustion event in real time.

For the first time, we can have a look right inside the very heart of an operating engine, and watch and record what happens when we change anything.

But let us get away from the unpleasantness of detonation, and look at a much more interesting plot of a power pulse, at a fairly high power setting (80%):

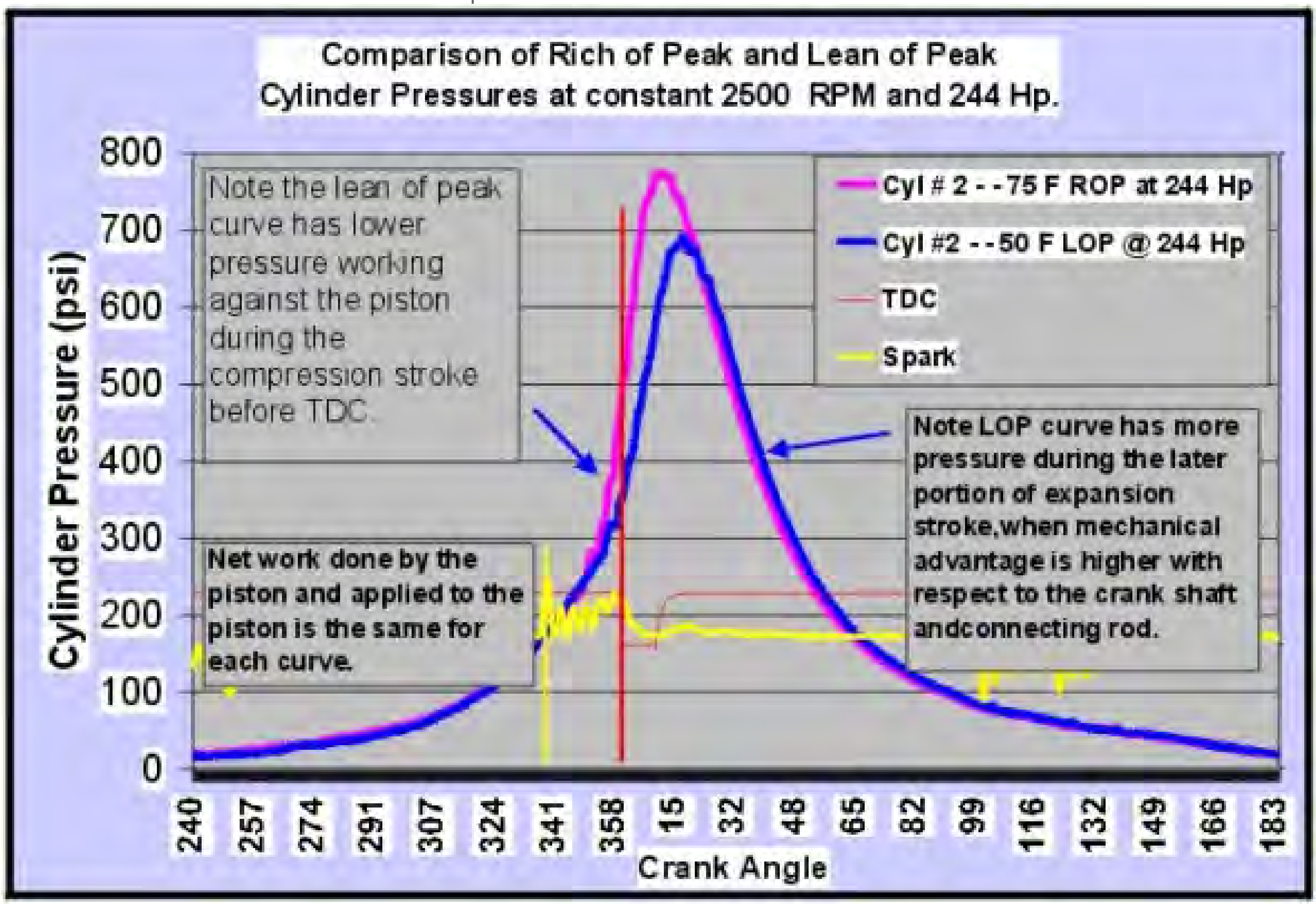


Rich of Peak (click for larger image)



Lean of Peak (click for larger image)

Comparison: Rich of Peak vs. Lean of Peak



Those two individual charts are pretty self-explanatory, thanks to the efforts of George Braly of GAMI, who prepared them for me. The one on the left does NOT represent a "desirable" power setting. The RPM and the mixture are such that the peak pressure occurs only 10.8° after TDC, and this will produce very high CHTs.

The one on the right is far better, even though the MP is much higher! The peak pressure is out at 16.2° after TDC. Fuel consumption is way down, and so is the CHT.

The third plot simply overlays the previous two. Same day, same engine, same flight, measurements taken within moments of each other. Both are at 244 horsepower (81%!), both at 2500 RPM, both show the same cylinder, on a turbonormalized TCM IO-550.

How can we tell that the actual power developed is the same for the two traces? Well, as a rough check, the airspeed produced was identical. But using numerical integration, the area beneath each trace can be calculated, and since the area beneath the pink trace is the same as the area beneath the blue trace, we know the power is the same. Additionally, by knowing the pressure, the RPM, and other factors, the horsepower can be calculated quite accurately.

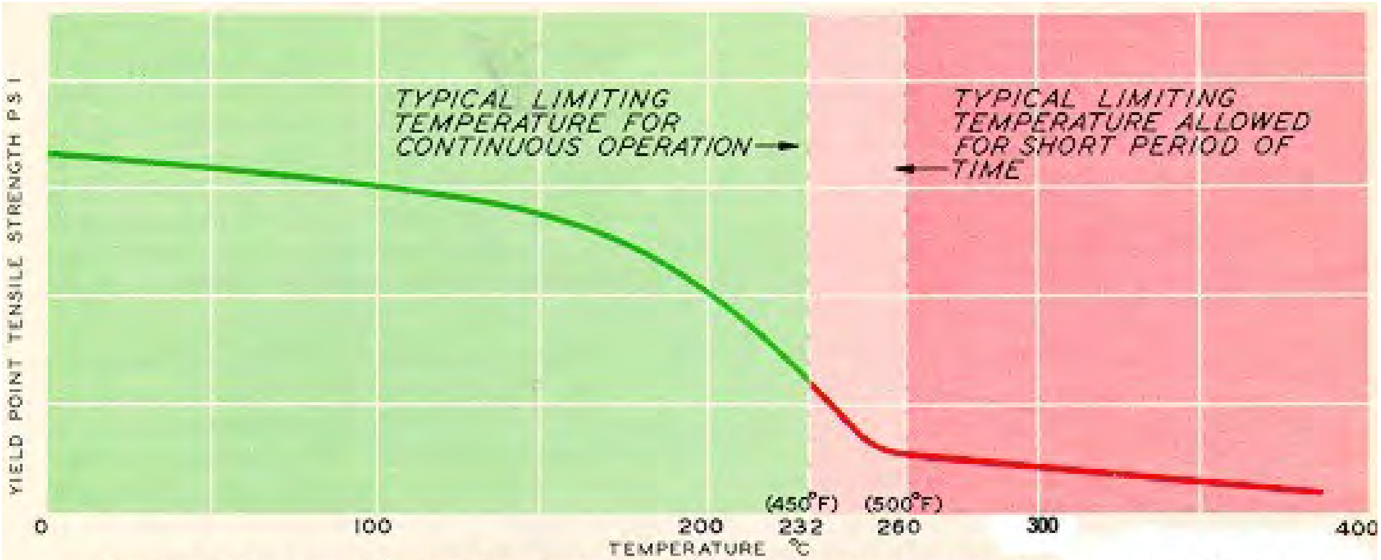
In effect, what happens is a longer, slower, gentler, and later "push." This shifts the mechanical advantage to a slightly better position, where a small change in angles makes a huge difference in effect.

Which combination is "better" to produce 244 HP? Well, the blue trace has a much higher manifold pressure, but CHT is about 35° F cooler. With cooler CHTs and lower peak pressure in the cylinder, which do you think is better?

How about CHT, Anyway?

CHT can be measured by a thermocouple washer under a spark plug, or by a probe screwed into a threaded boss in the cylinder head casting. The latter is probably more accurate. But there are wide temperature variations at different points around the circumference of the cylinder barrel, with some poorly-baffled cylinders showing up to 150° F difference between the hottest and coolest points! Poor baffling will also show up in large variations between cylinders.

But we've got to start somewhere, and again, the old manuals reflect a great deal of experience:



Strength of Aluminum Alloy vs Temperature (P&W "The Aircraft Engine and Its Operation" Page 19)

This chart from the Pratt & Whitney "The Aircraft Engine" shows what happens to aluminum alloy used in the cylinder heads and pistons of our engines. This is a scary chart, because it's obvious that even at normal operating temperatures, we've already given up a substantial amount of strength. The redline CHT on my IO-550 is 460° F, well out in the "short period of time" area. I would prefer to stay out of that region entirely, and looking at the sharp gain in strength going from 450° F to 392° F (200° C), I think the conservative pilot ought to limit CHT to that 200° C value, as much as possible.

There is some support for this. The P&W book goes on to say:

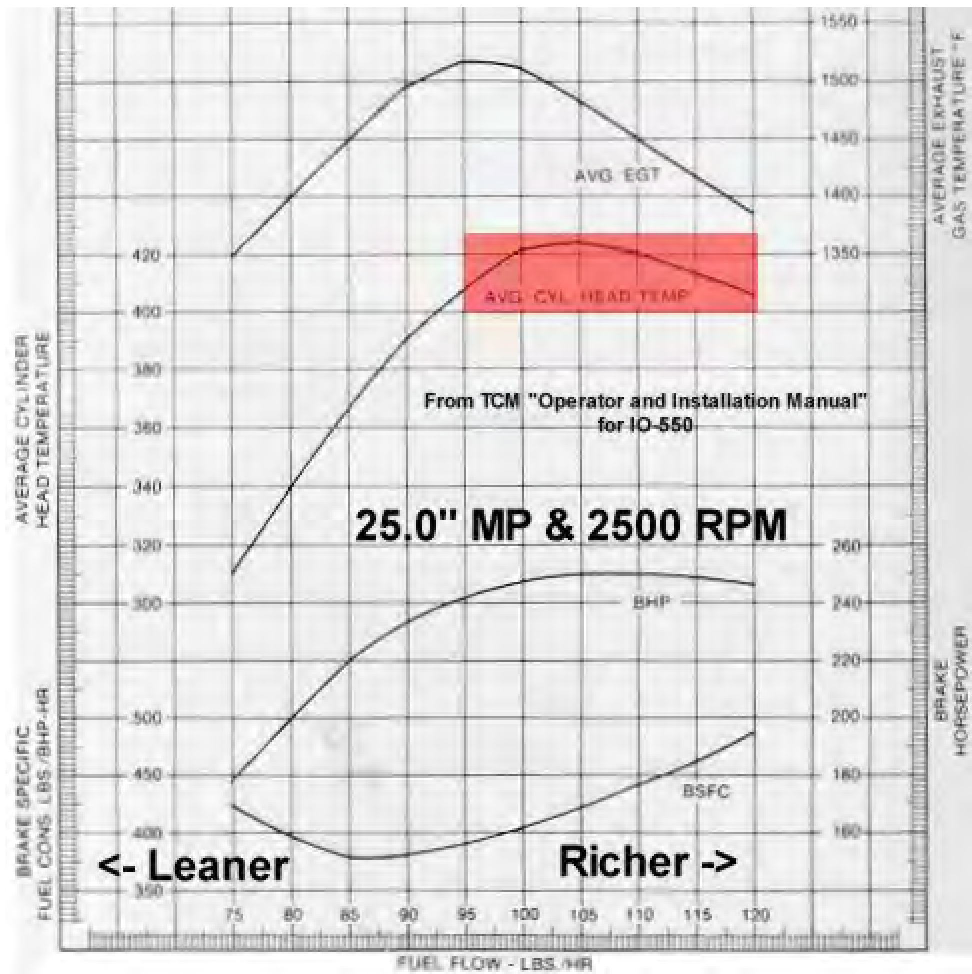
> "The higher limiting temperature (500° F) is for a restricted period of time, and is confined to take-off, to maximum performance in climb and level flight, and emergencies. The temperature limit for restricted operations should, therefore, be used for the shortest possible time only, and must never be exceeded.
>
> "The lower limiting temperature (450° F) is the maximum for continuous operation. It should never be exceeded except under the restricted operating conditions mentioned in the previous paragraph. It is sound practice to hold the cylinder head temperature 50° F (30° C) below this limit to keep the cylinder head materials at high operating strength." [emphasis mine.]

That puts us squarely at 400° F, a nice, easy-to-remember number.

There is more. GAMI has cemented thermocouples down in between the fins of a cylinder, tight against the barrel at the bottom of the grooves. While flying this at various temperatures, it was obvious that there is a variation around the circumference, even on a properly baffled and cowled engine. Furthermore, upon getting up around 420° F (at the probe), the CHT tends to become unstable, and tries to increase all out of proportion to whatever is going on. It seems pretty clear that at higher temperatures, the cylinder barrel goes significantly out-of-round, and since the piston can't change shape to fit, the piston starts scuffing the narrow part of the resulting oval, leading to the rapid rise in CHT. I have tried this on my engine, and the same "thermal runaway" seems to occur. I stopped it long before reaching much over 440° F, so I don't know how high it will go, nor do I wish to find out. By the way, the standard factory CHT instrument didn't show anything abnormal at all!

Personally, I have my JPI set to warn me if any cylinder goes over 400° F, and I try to maintain 380° F as a maximum to provide a margin. TCM suggests limiting normal cruise temperatures to 380° F in one publication, but then in another they suggest 420° F. Go figure. I'll take the lower value.

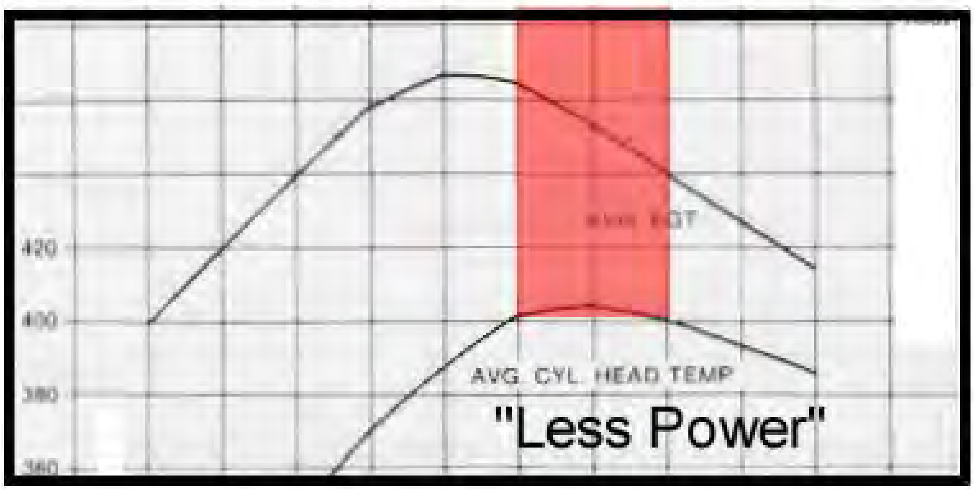
Let's re-visit that TCM chart of basic engine curves, this time with a red area to correspond to the above:

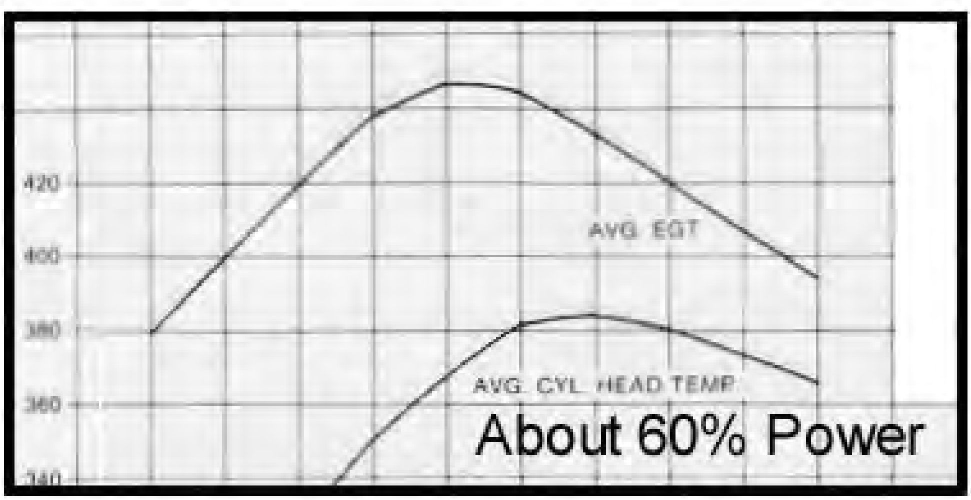


Remember that this is the chart of operating parameters at 25" and 2,500 RPM. Does that setting sound somehow familiar? Yes, it's the setting many have used for years right after takeoff, for climb power! The high temperatures are the direct result of pulling the MP back to 25", which cuts out the power enrichment feature of the fuel controller, leaning the engine dramatically!

This practice (pulling the throttle back after takeoff) may be the single most damaging thing many people do — with the best of intentions, to "make it easier on the engine!" Forget it, folks. Leave that throttle fully in, unless you need to make a substantial reduction in MP, maybe to 22", or so. (Remember, we're talking about normally-aspirated engines here.)

Let's take a little different look at those TCM curves:





The top picture is the same one we just looked at. I've cut out a lot of extraneous detail to illustrate my point. If we consider that area of CHT "off limits" because it's over 400° F, then the same area of EGT is also "off limits" because they go together. In this illustration, note there is no possible combination that will give us what we want, except very lean of peak, which would cost us a lot of power.

In the second picture, I've fiddled the CHT numbers, and erased the EGT numbers, to give a simple picture of some "Less Power." It's probably up in the 70% range, but that's not what I'm trying to show. Look at the much-narrower red band covering the peak CHT (be very careful to read "CHT" and "EGT" correctly, here in this text, and keep them straight while looking at the picture.) Now run up to the equivalent range on the EGT, and note where it lies on the curve? At this still-high power setting, peak EGT produces a satisfactory CHT! From this we should realize that "The Danger Zone" on the EGT is mostly on the rich side of peak – precisely where many factory documents would have us run. At higher power settings, we need to avoid peak CHT, which means avoiding some area rich of peak EGT.

(2004 note: Attendees at our seminar will hear this referred to as “The Red Box.”)

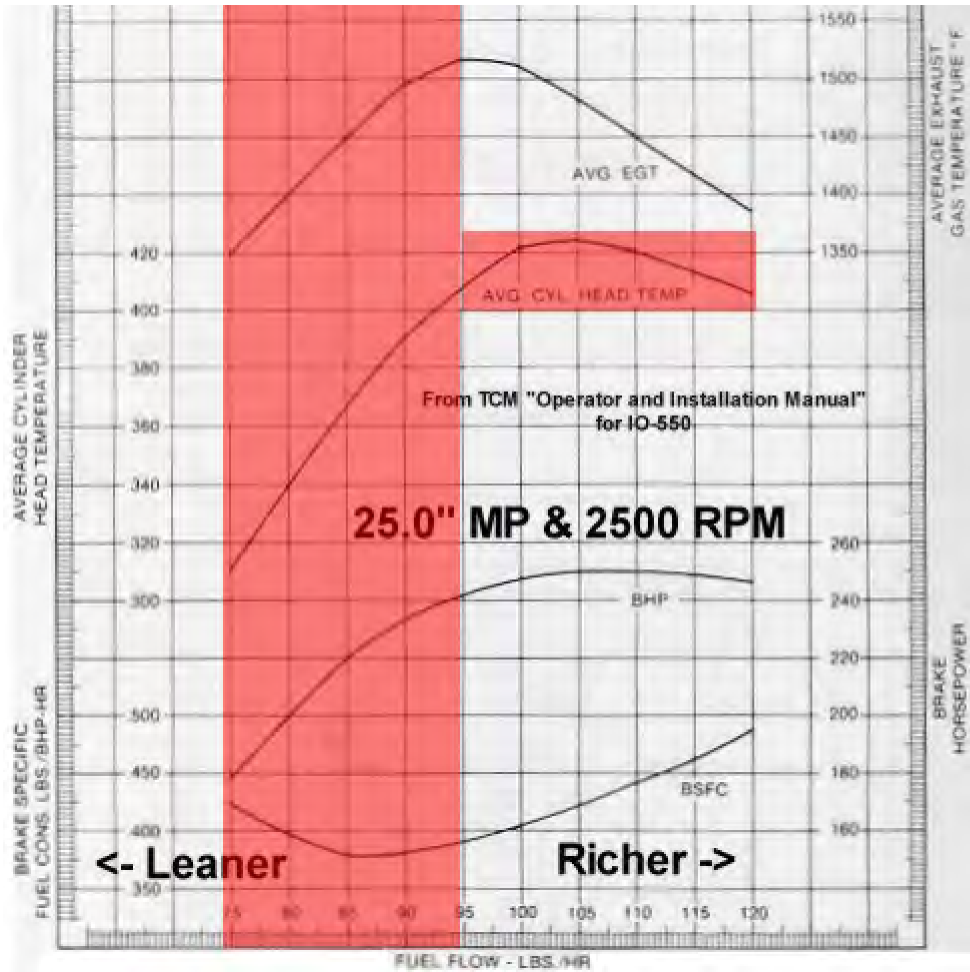
That Loose Formation, Again

Remember I talked about six (or four) cylinders, flying along in loose formation, all at different power settings? Now you may be getting the idea why I think that's important. No matter where you set your mixture on such a beast, most of the cylinders are <u>not</u> running where you think you set them! You have set <u>one</u> cylinder, and one only.

Now suppose you lean by the classic advice "lean 'till roughness occurs, then enrich just enough to restore smoothness." No one wants to run a rough engine, so this is good advice. A rough engine causes metal fatigue, pilot fatigue, sterility, baldness, imp …, but, I digress. I think we can all agree that vibration is a bad thing, all around. What's causing that vibration? Aha, I see that hand in back there in the audience. What's that you say? "Lean misfire?"

Sorry Charlie, no tuna. There's essentially no such thing as "lean misfire." It's probably a term some tech rep made up because he didn't know the right answer. A properly set up engine will tolerate leaning and remain smooth right down to that 30% power range (see combustion chart), at which point it just quits cold. There's no reason to shake, at all. Now that said, the real world is not perfect, and even well-set-up engines will show a just a tiny bit of roughness when leaned to the extreme.

What <u>does</u> happen to cause that roughness is that the first cylinder to peak and start down on the lean side will produce <u>less power</u> than the others, and unequal power from one cylinder (or more) <u>will</u> cause enough vibration to be obvious. So you enrich until the vibration goes away, restoring that one cylinder (or more) to approximately the same actual power as the others. That gets them all up on the "sort of flat" part of the power curve (see chart). There's no way of telling just where all that occurred, or what cylinder it was, but the resulting chart might look something like this, with a new red area added.



This second and much more serious red area holds true through the entire spectrum of power settings, so it is much more serious. Virtually all factory big bore engines suffer from this uneven power distribution, which sets an artificial limit on just how lean we can run. Uneven mixture distribution causes the entire lean-of-peak-EGT region to become a red zone, not available for use!

Some Old Wives' Tales (OWTs)

From this comes a few pernicious OWTs, all with a modicum of truth.

"Never run lean of peak!" That's right, you can't in most flat engines, because their uneven mixture distribution causes them to run too rough.

"Leaner is hotter!" That's true only up to the point of maximum CHT, which occurs at around 35° F to 50° F ROP for most engines. Leaning beyond that point makes 'em run cooler. Naturally, if your engine gets the shakes at lean mixtures because of poor mixture distribution and the resulting uneven cylinder-to-cylinder power, then the only leaning range left to you is on the rich side, and if limited to that area, leaner is hotter!

"Leaning too much will burn your valves!" True (at higher powers), unless you continue leaning to the lean side of peak EGT (where leaning makes cylinder heads and valves run cooler), or you operate at sufficiently low power settings that valve temperatures remain acceptably cool even at peak EGT. (This works out to around 60% to 65% of rated power, on most of the flat "big bores".)

These are the kinds of things running through factory tech reps' minds when they scream (as a Lycoming rep did to me awhile back), "I wouldn't recommend lean-of-peak to my worst enemy!" Neither would I, in his stock engine with its lousy mixture distribution!

There are, however, some alternatives.

What Do We Do about It; What *DO* We Do?

First, if you're going to operate one of these expensive big-bore engines properly, you must install an all-cylinder engine monitor, which at least tells you the CHT and EGT in each cylinder. If I had a four-banger, I'd put one in it, too, but that's more for troubleshooting.

(2004 note: At this writing, we think JPI makes the best hardware, with EI coming on strong, and Insight having dropped out of the running years ago (with rumors they may make a comeback. JPI and EI have very good customer support when it comes to warranty, service, upgrades, and repairs. All the manuals are extremely poor, with many errors of fact.)

Once you have that all-cylinder monitor, limit the hottest CHT to 400° F at all times. If it goes over that, increase airspeed (VERY effective!), open the cowl flaps a bit (if you have cowl flaps). Enrich the mixture if it is on the rich side, or lean it more, if on the lean side. But using extra fuel as a coolant should be your last-resort solution after the other things have been tried and fallen short.

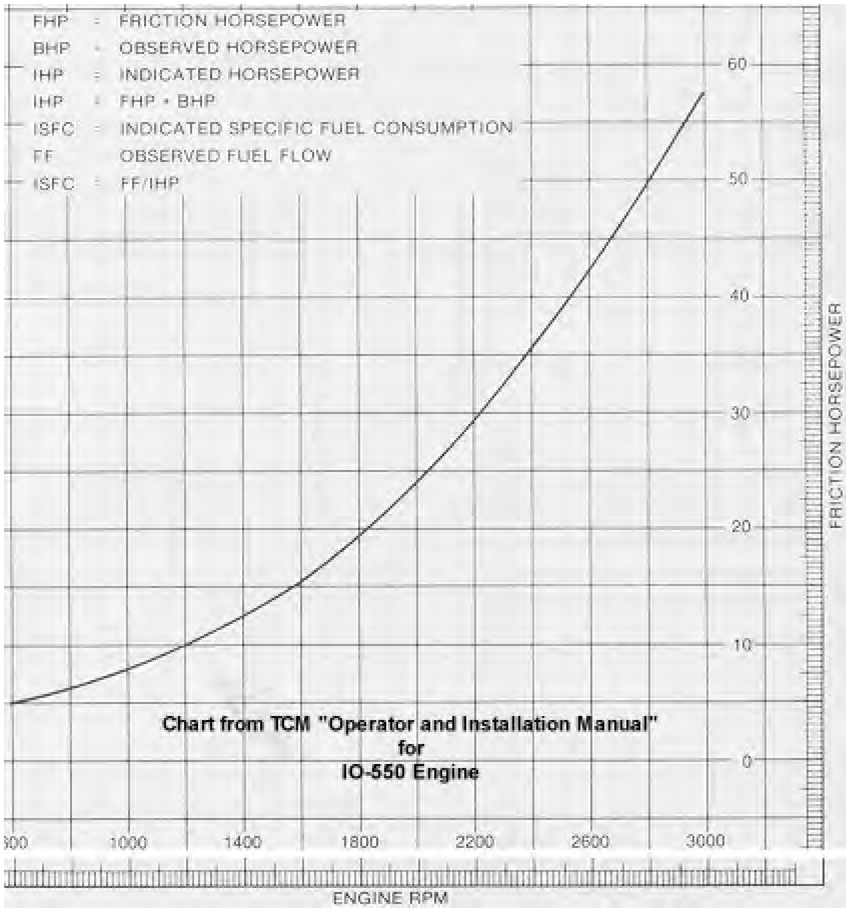
So far, most of this column has been discussing The Ideal Engine. Unfortunately, that doesn't quite exist, yet, and those with carbureted engines are really left out in the cold, except for the above two tips (engine monitor and 400° F CHT limit.)

(2004 data developed by Walter Atkinson clearly shows this to be in error.)

Here's another tip for carbureted engines, if you're operating high enough to use full throttle, or nearly so. From the full-throttle position, pull the throttle back until you observe the slightest drop in MP — perhaps a quarter-inch or less. Leave it there. That will cock the throttle plate a little, just enough to set up a vortex that will cause better atomization and mixing of the fuel and air. (This is counterproductive in fuel injected engines.)

(2004 note: This old trick is indeed somewhat helpful. But a far more useful trick is to fiddle with different carb heat settings to find one that causes better vaporization and atomization. With the correct carb air temperature, fuel distribution can be very, very good indeed.)

In principle, we should all operate at the lowest possible RPM allowable for the MP, and the following TCM chart shows why.



As you can see, the losses to friction are about 37 HP at 2,500 RPM, and about 27 HP at 2,100 RPM. That's 10 very useful HP, in my opinion.

However, this low RPM stuff must be tempered a little bit, by the fact that decreasing RPM moves the PPP closer to TDC. Anytime we move that PPP away from that ideal 16° to 18° after TDC, we're losing power, and increasing CHT. On the other hand, the leaner we run the engine, the more we delay the PPP, getting it further from TDC.

From this we can see that there must be a balance between slower/leaner, and faster/richer. <u>For high power, maximum-performance operation, you should run richer mixtures and higher RPMs. For low power, maximum-efficiency operation, you should run leaner mixtures and lower RPMs.</u> It would be really nice if we could develop some sort of "super linkage" that ties the prop control and mixture control together into sort of a single-lever power control, but that would be a formidable design task. It appears to me that running in accordance with the POH will provide good results in the worst possible cases, and TCM probably felt this was their best option.

Fuel-Injected Big Bores

With big-bore fuel-injected engines like TCM 520s/550s and Lyc 540s, we're getting some modern developments that can be of major benefit, and which will pay for themselves in short order. These improvements should also allow safe and efficient operation well outside the suggestions in the various POHs and manufacturers manuals, including much lower RPM, higher MP, and leaner mixtures. At low altitudes, I am routinely running my IO-550 at

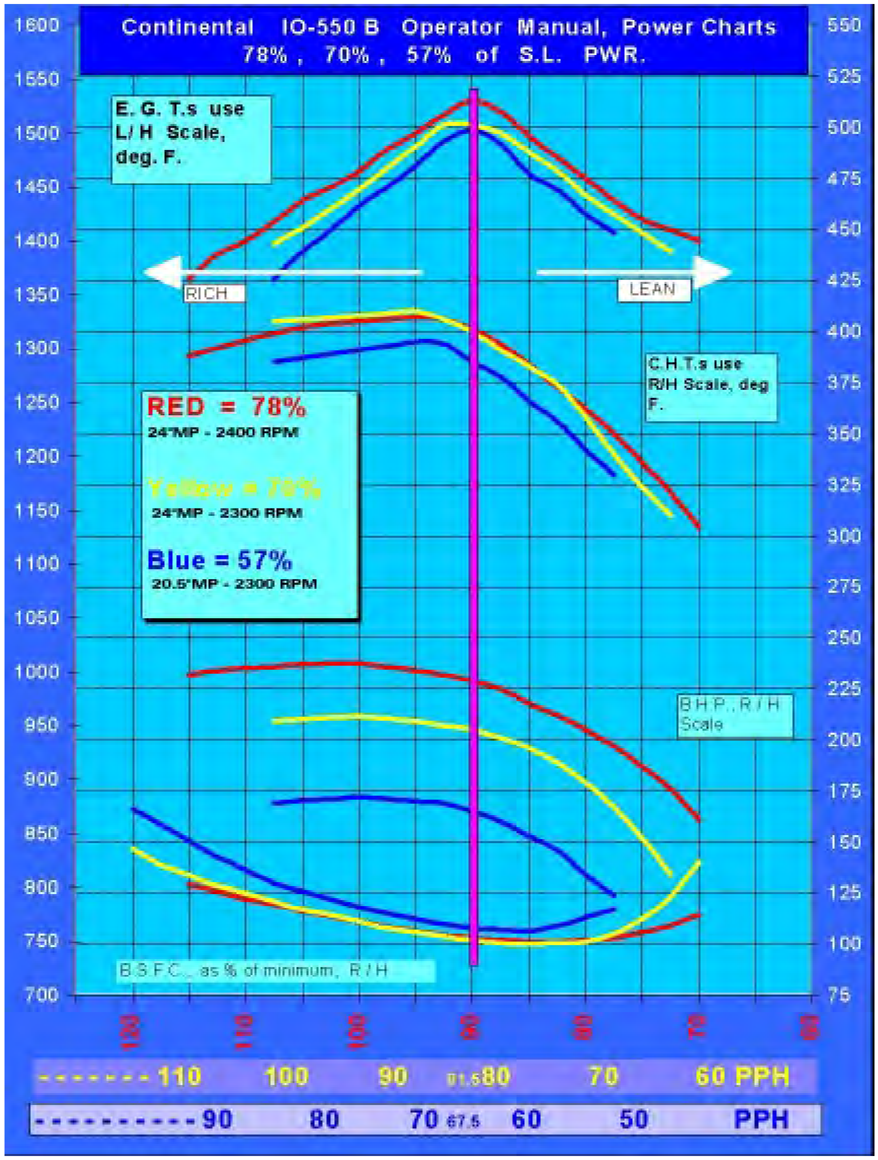
2,100 RPM, full throttle, and very lean, perhaps 50° F LOP EGT. That produces about 75% of rated power. The engine appears to love it, runs very cool, makes much less noise, and runs very smooth. However, those settings would be a deadly combination if I enriched the mixture, or even worse, tried running ROP. I also cannot climb at that power setting, because the loss in airspeed causes too much increase in CHT.

Once you have the all-cylinder engine monitor installed, the next best thing you can do for your big-bore flat six is to install GAMIjectors™ from General Aviation Modifications, Inc., in Ada, Oklahoma.

The usual disclaimer: I own no stock, directly or indirectly in GAMI. I wish I did. I do not work for them. I wish I did. I do not benefit in any way from the sales of their products, and I paid full-boat retail for my own GAMIjectors™. The owners have become personal friends, and are men that I admire greatly. I have been very distantly involved with them in some very minor testing and comment.

GAMIjectors™ are custom injectors that match the fuel flows to the air flows in all cylinders. With these, you can quite easily lean your engine right down to starvation levels without roughness. This means you cannot use the old trick of "lean 'till rough, enrich 'till smooth" because the engine never gets rough at any mixture setting. Your engine will run cleaner, cooler, and smoother, and you will be able to use the full range of mixtures, just as the operators of the big old radials did for several hundred million hours in a bygone era. Oh, by the way, there is <u>no evidence whatsoever to support the OWT that lean mixtures cause corrosion in exhaust stacks.</u>

When you lean an engine with *GAMIjectors™* , you will see all EGTs rise at the same time. (The absolute temperatures may be different from one cylinder to the next, but that's unimportant.) All should peak at the same time, and all should fall at the same time. This will produce results as in the following chart:



By this simple, one-hour installation, we bring our current engines up to very nearly the standards of "The Ideal Engine" I have discussed at length above.

Going well beyond that, GAMI is currently deep in R&D running test engines. This effort promises to give us all a better ignition system. No, not the junky current "state of the art" automotive style electronic ignition systems for our aircraft, but a simple, safe, certified system that will leapfrog all existing technology. For the first time, there will be a system that fully controls what is happening inside the combustion chamber.

I haven't seen this experimental system run yet, but George and Tim at GAMI have invited me to come see it, and have a little Oklahoma BBQ, too. There are rumors that it may even cure/prevent baldness, loss of memory, cancer, and the common cold!

(2004 note: Please remember, the above was written in 1999! Since then I have indeed seen PRISM run, and so will you, in the seminar!)

Be careful up there!