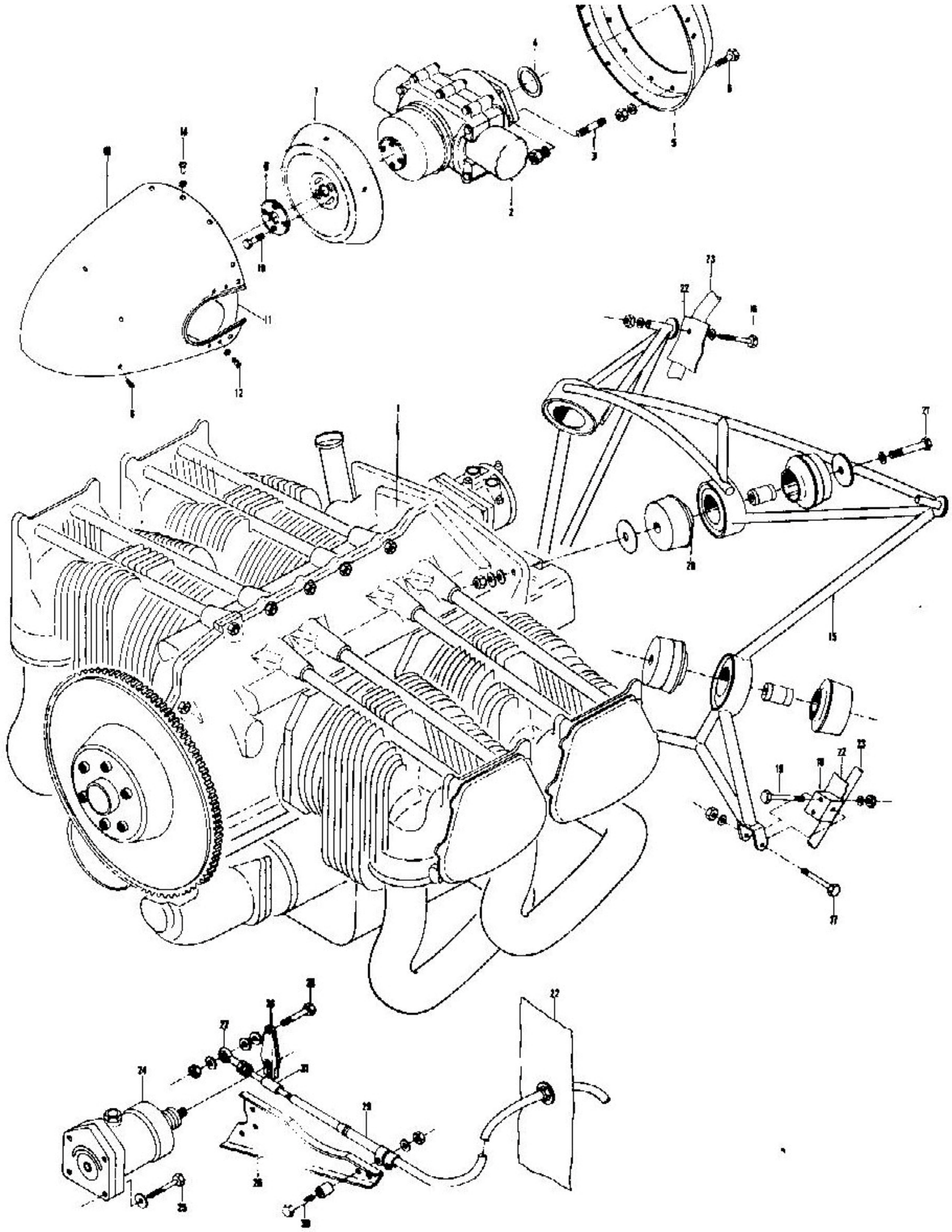
Power Management: A Typical Flight

Apologies in advance, this will be a long one. I hope it is of some use in the general how-an-engine works discussions, but no guarantees. I'll have to gloss over a lot of stuff to keep it under control. The specific engine and airplane I'll be discussing is my beloved 1964 Mooney M-20E with a Lycoming IO-360 engine; variants of both continue in production to present-day. (You can google a picture). (I sold this plane in 1998 to partially pay for another addition to my ex-wife collection.) The automotive analogue might be a 1970 Porsche 911S – performance coming from small size, light weight, and low drag, vs. say a 1970 Camaro's raw horsepower. The M20E is a four seat, retractable landing gear, high performance (by FAA definition) aircraft. Besides my familiarity with flying it, it also serves as a good example because, except for navigation and communications, there are no electronics of any kind to help you out. The engine is a horizontally-opposed flat 4 cylinder of 360 cubic inches (5.8 liters) rated for 200 hp at 2700 rpm. If this seems pretty feeble, consider that the rpm is limited by the propeller tip speed and that it will make this power all day long. I believe the certification test requires a continuous ~100 hours at full power with no damage or degradation of any sort. (Don't try this with your Renny's guys!) Reliability, safety, and weight are the primary design drivers, not technical gimmicks, peak power, or (unfortunately) cost. It's mechanically fuel injected, uses two completely separate ignition systems powered by magnetos, and has an engine-driven primary fuel pump. As a consequence and by design, it will run quite happily with no support from battery or generator. The cylinders are air-cooled (no water pumps to worry about) with the rest being essentially oil-cooled. Oil capacity is 8 quarts though it will run fine if it has to, on 3 quarts with reduced power. Recommended oil change intervals are 50 hours (~7,500 airplane miles), though at about 30 hours the oil consumption goes up markedly, so I used 25 hrs or so. Time-between-overhauls (TBO) is given as 2000 hours (300,000 miles), though that is seldom reached without some cylinder and valve re-working. Weight is given as 323 lbs.

Here's a line drawing:



Notice that the propeller hub is included, as well as that little gizmo at the bottom of the picture. Engine oil is provided from the front of the crankshaft, which is hollow, at a pressure regulated by the prop governor. This is essentially a “CVT” type transmission which adjust the pitch of the propeller based to keep the engine at a constant rpm set by the pilot.

Here’s a picture of airplane no-good piston on my kitchen counter next to a universal object for size comparison:

Two points here, first, the thing is huge! Even with dual spark plugs, the flame front has a long way to travel before covering the whole combustion chamber (should sound familiar to 13B owners) and thus it's easy to get into a detonation condition, which is a bad thing to do while flying. Second, the new replacement for that piston costs $600 and with pin and rings is pushin $1k. A crankshaft is about $15k, camshaft, $4k, a crankcase, $20k. Even just a good sparkplug is $90 *each*, so a fresh set of plugs on this engine is $720. A pilot/owner is highly motivated to not mess up his engine, but as we'll see in a moment, it's really easy to do just that.

Ok, let's go for a flight and see what power management is about. The 'big three' engine controls are throttle, prop speed, and mixture. They are generally "plungers" that move in and out of the panel near the middle of the plane, with a 'fine-tuning' vernier screw that lets you rotate the knobs on the end for fine adjustments. Full back is roughly "off" and full forward is roughly "full out". (It's where the phase 'balls to the wall' came from.) The cowl flaps should be open (they regulate air-flow through the engine compartment) and the alternate air should be off (it provides a reserve airpath in case the air filter should become blocked). Assuming a cold engine at reasonable outside air temperatures, you first turn on the master electrical switch, which connects the battery to the electrical system. No airplane has any kind of choke (presents a place for ice to form), so we gotta 'prime' the engine. To do this, flip on the electric auxiliary fuel pump (which also provides a backup to the main fuel pump) which pressurized the fuel system against the closed mixture control. Shove the mixture control forward, which opens the valve, supplying fuel right through the fuel injectors, count 'one potato', and pull the mixture control to idle cutoff. Do it too short and the engine won't start. Do it too long and the bottom plugs will foul and it won't start. Do it way too long and the engine will fire backwards, light the puddle of fuel under the plane, and burn the sucker to the ground (I watched a guy do this once.) The key switch is very different than a car, with off-left-right-both positions, plus a 'push' which engages the starter. 'Both' un-grounds both magnetos and lets them fire. In every way, save one, magnetos *suck* and they are at their worst when spinning slow, like for a start. Ok, so aux pump 'off', mixture full rich, say a minor prayer and hit the starter. Yeah it's running! Now get it moving ASAP, cause engine cooling is really bad at a standstill and even at our ~15 mph taxi speed. The good news though is that it helps get the engine warmed before takeoff. Ideally you want a fast idle of about 900-1000 rpm to keep the plugs clean, but that's not always possible. Near the end of the taxiway, there's usually a widening of the pavement called the 'run-up area'. Pull in and that's where the final engine checks are done. Brakes set, increase the throttle to 1700 rpm, then test each magneto individually for functioning. On a single magneto, there should be no more than a 125 rpm drop. If there is, a plug is likely fouled and you get to do a song-and-dance with the throttle and mixture control to clear it. If it can't be cleared, you're done for the day. Mag check ok, then increase to 2000 rpm and cycle the prop control briefly by pulling it back and pushing forward again immediately as the rpm drops. This cycles warm oil into the prop hub and governor. Pull it back too long and far in this condition and you're gonna wreck your engine. Where are the temps? If the cylinder head temperature is too cold, then the tapered cylinders haven't expanded enough at the top to allow the piston to move freely under the heat of full power with resulting damage or engine failure. And as you all know, full power on cold oil is a bad idea.

'Cleared for takeoff', let's go. A nice wide, gentle sweep onto the runway (in some planes with a partial fuel load, you can suck a bubble of air into the fuel lines if the fuel sloshes away from the pickup port), aux fuel pump 'on', ease in the throttle (mixture is 'in' at 'full rich', prop is 'in' for max rpm). Besides the usual pilot stuff, I'm looking to see around 28"Hg of manifold pressure at 2700 rpm. Rotate at 60 mph, ease off at 80, get some ground clearance, haul up the gear, let it accelerate to 105 (best rate-of-climb speed) pull back and trim the yoke pressure to maintain that speed, and at 500 ft or so, start transitioning into cruise-climb: flaps 'up', aux fuel pump 'off', cowl flaps 'half-closed'. Going through about 1,500 feet, pitch down a little, let the climb rate decay a little and pick up 120 mph. From takeoff, now, and through just before landing, *the throttle does one thing and one thing only: it controls the manifold pressure. The propeller control does one thing and one thing only: it sets the engine rpm.*

Time for the first power reduction. When reducing power in flight, you *always, always, always* pull the throttle back first, and the prop control second. Do it the other way around, and you can blow your engine. For cruise-climb, I pick 26"Hg and 2600 rpm. Why, see my "Cliff Notes" power chart which summaries the official charts.

POWER SETTINGS (RPM vrs. Manifold Pressure)

	RPM	2700	2600	2500	2400	2000	1900	1800	
	TACH SET		2550	2470	2380	1980	1890	1800	
	Max MP	28.5	28.6	28.7	28.8	26.1	25.5	25.0	
	(%)								(BHP)
	100	28.5							200
	95	27.4	28.2						190
	90	26.3	27.1	28.1					180
	85	25.2	25.9	26.8	28.0				170
	80	24.0	24.8	25.6	26.6				160
	75	22.9	23.6	24.6	25.4				150
	70	21.8	22.4	23.2	24.1				140
**	65	20.6	21.3	22.0	22.9				130 **
	60	19.5	20.2	20.8	21.6	25.8			120
	55	18.4	19.0	19.6	20.3	24.2	25.5		110
	50	17.2	17.8	18.3	19.0	22.6	23.8		100
	45			17.0	17.8	21.0	22.0	23.5	90
	40					19.3	20.4	21.8	80
	35					17.8	18.8	20.0	70
	30						17.0	18.2	60

FUEL FLOW (RPM, BHP, & GPH)
(Manually Leaned to Best POWER)

	RPM	2700	2600	2500	2400	2000	1900	1800	
	(%)								(BHP)
	100	15.7							200
	95	15.0	14.8						190
	90	14.4	14.1		13.8				180
	85	13.8	13.5		13.2				170
	80	13.1	12.9		12.5				160
	75	12.5	12.2		11.9				150
	70	11.9	11.6		11.3				140
**	65	11.2	11.0		10.7	9.9			130 **
	60	10.6	10.3		10.1	9.3			120
	55	10.0	9.7		9.4	8.8			110
	50	9.3	9.1		8.8	8.2			100
	45	8.7	8.5		8.2	7.7			90

FUEL FLOW (RPM, BHP, & GPH)
(Manually Leaned to Best ECONOMY)

	RPM	2700	2600	2500	2400	2000	1900	1800	
	(%)								(BHP)
	75	10.7	10.4		10.1				150
	70	10.1	9.9		9.6				140
**	65	9.6	9.4		9.1	8.5			130 **
	60	9.0	8.8		8.6	8.0			120
	55	8.5	8.3		8.0	7.5		7.3	110
	50	8.0	7.7		7.5	7.0		6.8	100
	45	7.4	7.2		7.0	6.5		6.3	90
	40					6.0		5.9	80
	35					5.5		5.4	70
	30					5.0		5.0	60

The top 1/3 gives power as a function of manifold pressure and rpm, the middle third, fuel flow with the mixture set ‘rich’, the bottom 1/3, with it set ‘lean’. Let’s deal with top 1/3 for now.

Full power is 2700 rpm @ 28.5”, shown at the top left. 30% power is 1800 rpm @ 18.2”. Decide what power you want, and to first approximation, adjust throttle (mp) and prop (rpm) to get it. Simple? Not quite yet. Suppose in my power reduction above, I get a little silly and at full throttle (2700 @ 28.5”), I pull the prop control back to 2000 rpm. Try to find 2000 rpm @ 28” on the chart … *it ain’t there!* Move your engine into the upper left part of the chart and it’s gonna detonate. It’s the equivalent of stomping on the gas in 6th gear at 10 mph, though in modern cars, the engine control unit will likely save you. Not so in this airplane. I’ve seen cylinders blown clear off an airplane engine when this happens, which tends to make the rest of that flight very interesting. Also notice, as a complete accident of measurement units and mechanics, that every single “square” setting is in the safe operating range (with an exception).

2700 @ 27” is ok, so is 2600 @ 26”, 2500 @ 25”, on down to 1800 @ 18”. For a quick and dirty adjustment without looking at the chart, a “square setting” is always ok … almost. The exception is in that blank space between 2400 and 2000 rpm which contains a forbidden zone about 200 rpm wide. (I give it a wide berth.) Continuous operation in that range with this engine can set up a torsional vibration with the particular installed propeller which can destroy the prop or the crankshaft, with consequences ranging from expensive to fatal. The under-square case, like 2400 @ 10” is always safe whether it’s on the chart or not, where is the over-square condition may or may not be, so 2400 @ 28” is ok, but you’d better check. On a turbo-charged engine it is much much easier to end up in the detonation range than this chart shows.

So back to the flight, still climbing at a sedate 120 mph. At the setting 2600/26” the power is 85% of max, but already by 3000 feet, the mp is noticeable dropping off, requiring the throttle to be opened more to compensate for the drop in the outside air pressure. With the drop in air density, the fuel/air mixture is also getting more rich, so I pull the mixture knob back carefully, until I see a small rise on the exhaust gas temperature (EGT) gauge. You can actually feel the power increase as this is done. By about 4000 feet the throttle is fully open and further increases in altitude cause a reduction in engine power from that 85%. With a turbo, we could start closing the wastegate and fix avoid that power loss. One can see this effect on the right hand side of the following chart.

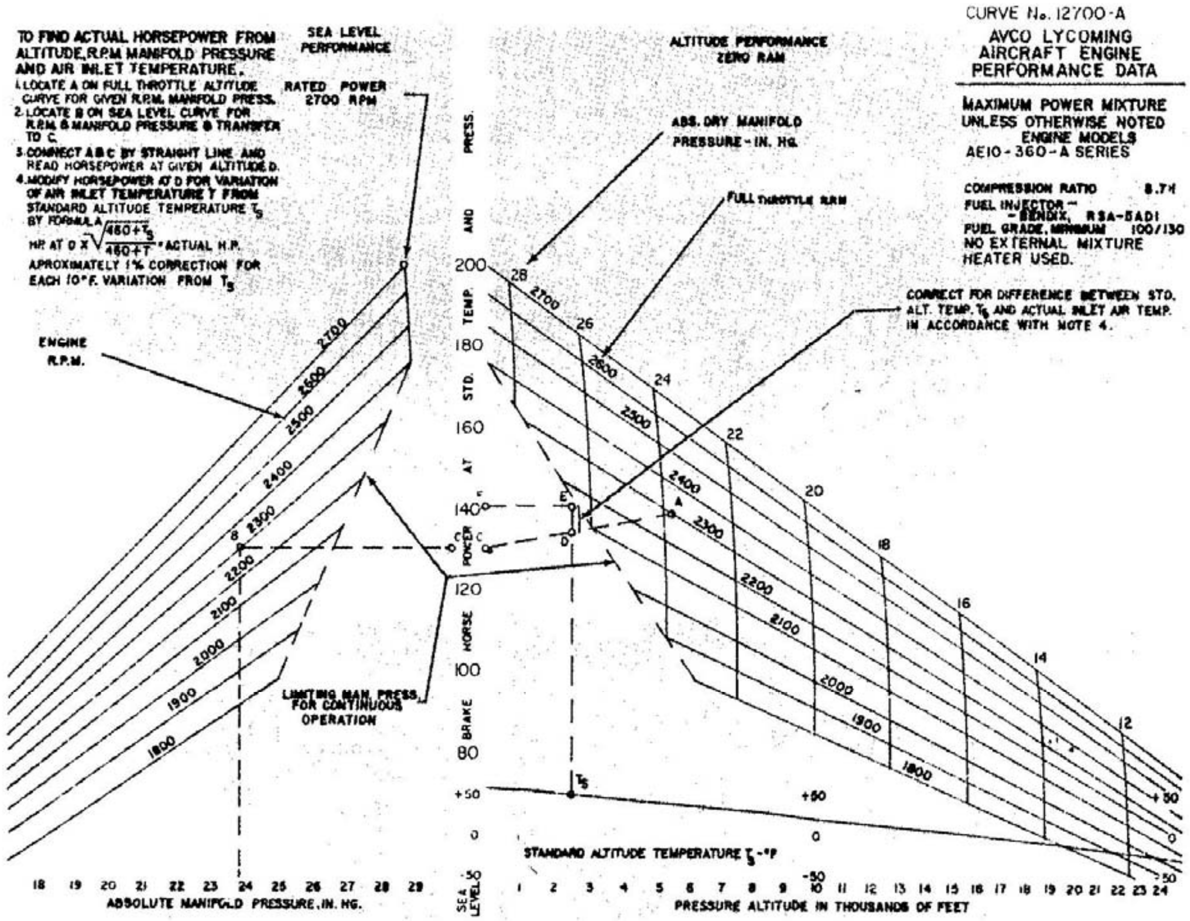
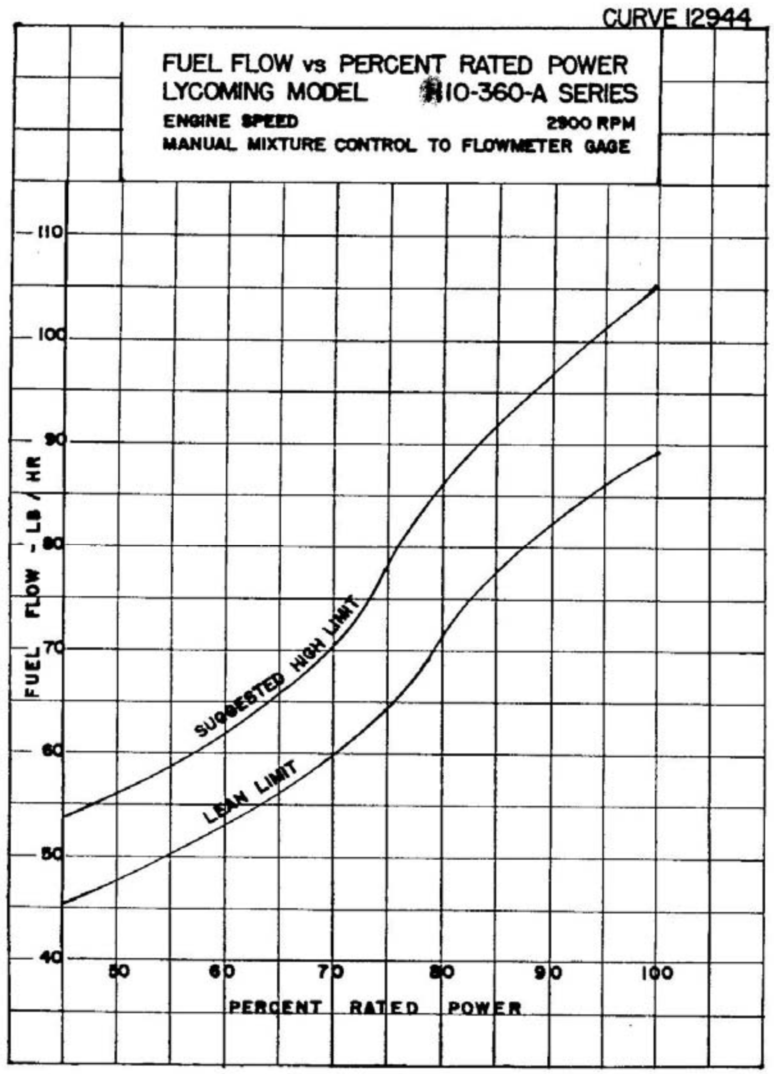


Figure 3-21. Sea Level and Altitude Performance - IO-360-A, -C, -D, -J, -K; AIO-360 Series

The left side of the chart is the information partially summarized in the "Cliff Notes" version above. If you pick 170 hp (85% power), move to the right until the line intersects 2600 rpm and then go down, you hit 5000 feet as the highest point at which you have enough mp to get that power. The higher we go, the less air resistance there is and the less drag there is on the airframe, but also the less power we can make. Suppose we want a pretty fast cruise, but don't want the fuss and wear of 2600 rpm. At 2500 rpm, the highest altitude we can still get 75% power (which is the normal 'high cruise' setting) is around 7500 feet. This is a typical 'sweet spot' for NA aircraft. For turbo'd planes, this spot can be much, much higher, but then you're sucking oxygen, followed by special flight rules above 18,000 feet. So, we level off at 7500 and reduce engine rpm with the prop control, to a reading of about 2500 @ 24" (safely under-square). With the need to climb further removed, the speed picks up to around 175 mph (I'm not going to get into true vs. indicated airspeed here.) We're going really fast and it's really cold outside, so the cowl flaps are now closed. Now it's time to properly set the mixture (air/fuel ratio).

The reason for doing so is shown in this chart:



Fuel flow is given in pounds/hour, where 6 lbs = 1 gallon. At 75% power, the difference in fuel burn between the rich and lean settings is close to 20%, almost 4 gallons/hour. Finding the lean-tune can be described with the help of the following chart:

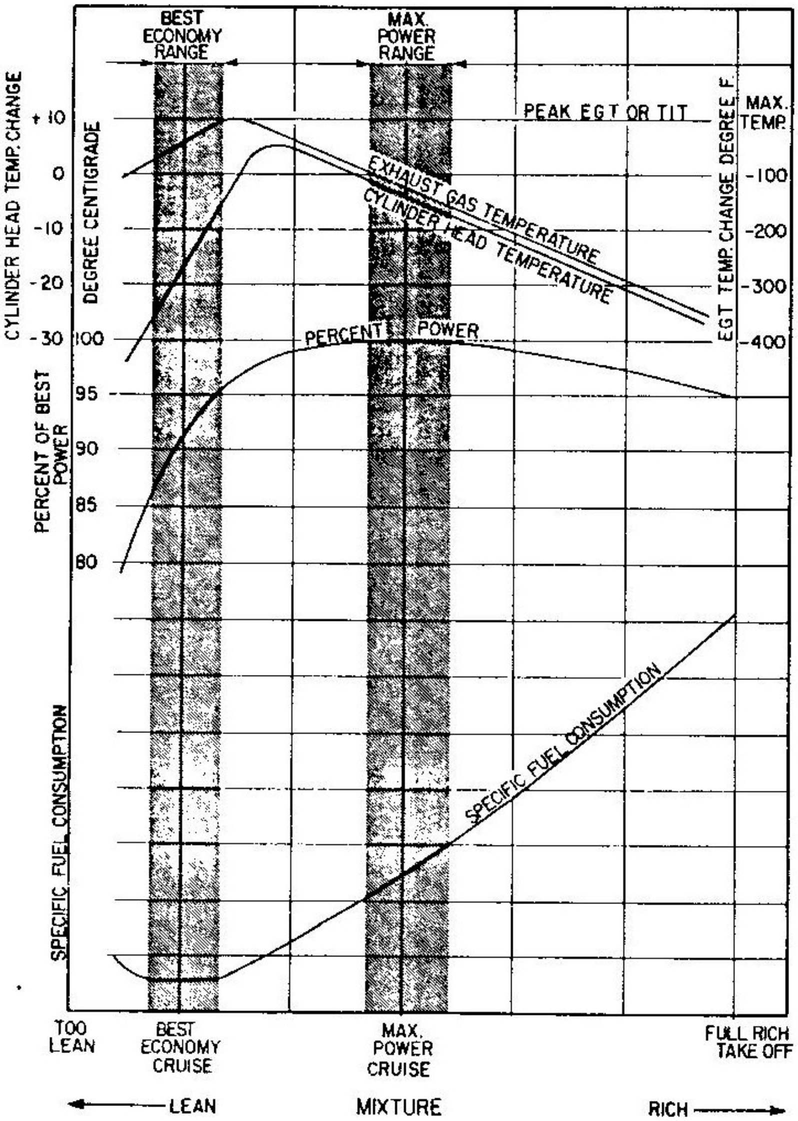


Figure 3-1. Representative Effect of Fuel/Air Ratio on Cylinder Head Temperature, Power and Specific Fuel Consumption at Constant RPM and Manifold Pressure in Cruise Range Operation

Up to this point, the engine's been running on the right, 'rich', side of the chart, even though we've done some initial leaning. Now we ease the mixture control ever so slowly back while watching the exhaust gas temperature (for turbo's it's called the turbine inlet temperature or TIT – no cheap jokes please!). On a NA engine in good health, the peak will be comfortably below the allowed limit, the turbo'd guys have to be careful. Establish where the peak is. For lowest fuel consumption, we want to be about 50 F on the lean side. For best power, about 125 F on the rich side.

Now we're kinda done for a while, motoring along, enjoying the view, burning about 10 gph at 175 mph or 17.5 mpg. If you want to lollygag along at 120 or so, set up 30% power, 1800 rpm @ 18", with 5 gph, which is 24 mpg. Pretty amazing really; these M20's are really low drag machines, which presents all kinds of problems when it's time to come down. [As an almost-aside, this particular series of planes have a feature called "power boost". Once you're above the haze layer, where almost all of the dirty air is trapped, the outside air is very clean. By pulling a knob, you have the option of bypassing the air filter, and getting a direct blast of 175 mph air straight into the injector body throat. In practice, this results in an increase of about 1.5"Hg of manifold pressure which, taken from the charts about a 6% increase in achievable power. Free is good and it's sometimes useful. However, compare this to some of the claims made for car induction systems. The dynamic pressure of air at 60 mph is 1/9 that of air at 180 mph. The plane's getting a 6% boost, the car at best gets a 0.6% ram-air effect. Hummm ….] Now don't fall asleep and forget to manage the fuel supply. Airplanes generally have 2 or more fuel tanks. Running a tank dry can put the plane seriously out of balance and, of course, the engine quits. The prop keeps it spinning, but no gas = no power. If you're lucky, nothing got damaged as the mixture leaned out right before stopping. If you're lucky, you didn't suck so much air into the system that you hit the ground before the engine starts again. If you're thinking (which you weren't doin when you ran the tank dry), you remember to reduce the throttle before switching to the full tank, so the slut of gas doesn't send a cylinder flying off when it works its way through. In this case, silence is the best waker-upper ever, and no, don't ask me how I know this.

There is a huge amount of potential energy stored up during our climb in the form of altitude. When it's time to descend, and I lower the nose, that energy manifests itself by increasing speed. The redline airspeed is 198 mph and it doesn't take much of a descent rate to run the speed right to redline, so the power has to come back. Reducing power reduces the heat output of the engine, but cooling power of already-cold air at these speeds is tremendous. A dramatic power reduction in this situation can easily result in a matched set of cracked heads and a $10,000 repair bill. We have to hit a target point near the airport, which let's assume is near sea-level, at the gear down limit of 120 mph about 1000 feet above the airport (assuming a visual approach). Later Mooney's have speed brakes to allow descent without major power reductions, but this one is not so fortunate. So, richen the mixture to peak EGT to maximize heat production, ease the throttle back to 20" and the prop back to 2400 rpm. This is around 55% power, which should allow about a 300 feet per minute (fpm) descent at around 180-190 mph. When do we have to start down? In this case, we have to blow off about 6500 feet, which at 300 fpm is 22 minutes, or at 180 mph, *66 miles*! On top of that, we're gonna reach that 1000 ft high traffic pattern way too fast and it takes even more space to get it slowed.

In terms of engine management, it's a balancing act all the way down. Entering thicker air means the mp wants to increase, so you're constantly easing back on the throttle to compensate. You also have to keep richening the mixture – forget to do so and the engine can get so lean as to cause damage. Toward the end, reaching the target altitude is easier than reaching the target speed. Remember, this thing can do 120 (at these low altitudes) with maybe 40% power. Something's gotta give. Back the power down to 30%, cross-control to plane to add drag, or sneak in some steep turns for the same reason. Once the gear is down, the drag increases enough that the power can be increased as needed.

Entering the traffic pattern near the airport, we have to get ready to take off again. We could blow the approach, or a sudden obstacle may appear on the runway at the last moment. (I've had the following happen: another airplane pulls out, another airplane tries to take off the wrong way, a fuel truck crosses, a construction truck crosses, a wildebeest crosses (in Africa), a golf cart crosses, a deer crosses, a hunter shooting at the deer starts firing across the runway at the deer who just crossed, and, the all time winner, a line of tanks starts firing across the runway (Switzerland)). So, prop 'full-forward' (the throttle is nearly closed), mixture 'full-rich', aux fuel pump 'on'. Land, and we're done … almost. Turn the aux fuel pump 'off' or you'll cook it at an idle fuel flow. Open the cowl flaps or you'll cook the whole engine on the taxi back. Park, throttle up to 1500 rpm or so, then pull the mixture control to 'idle-cutoff'. Shut the engine off with the 'key' and you won't get it started again before pulling and cleaning the plugs. Done!

Okay, hopefully you have no only some idea of how these engines are operated, but a greater appreciation for what those wonderful electronics are doing for us in modern cars. Supercharging in any form makes engine management, whether manual or electronic, much more complex and much easier to do something bad. Here's one final chart that shows something of that complexity:

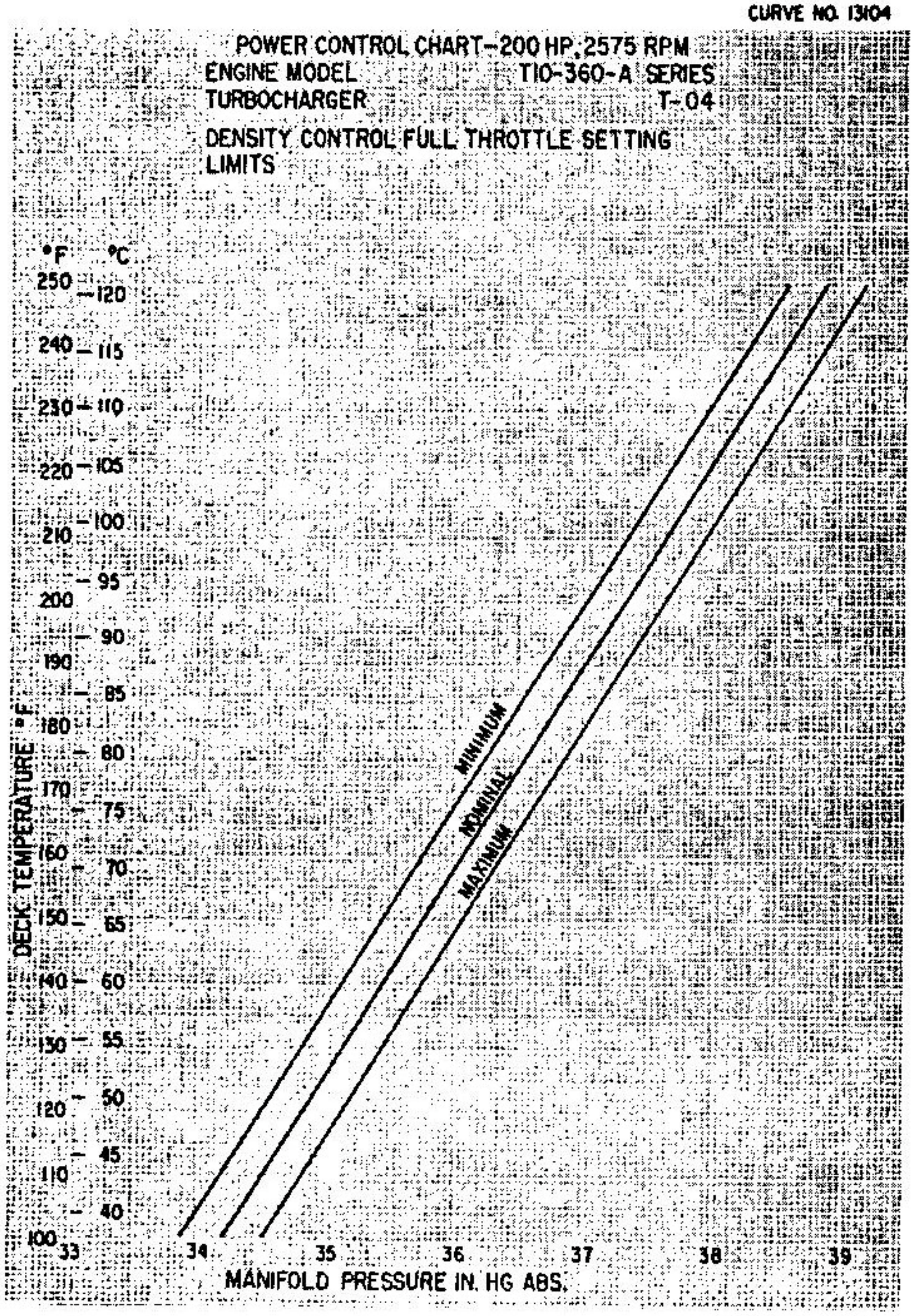


Figure 5-3. Density Control Full Throttle Setting Limits

Here, the maximum, full-throttle manifold pressure allowed is shown to be quite strongly influenced by "deck" or core engine temperature. For a fixed volume and pressure, there is less air mass at a higher temperature than at a lower temperature which is allowing a higher manifold pressure at higher temps than lower.

YMMV.