HOW SLICK IS YOUR AIRPLANE?

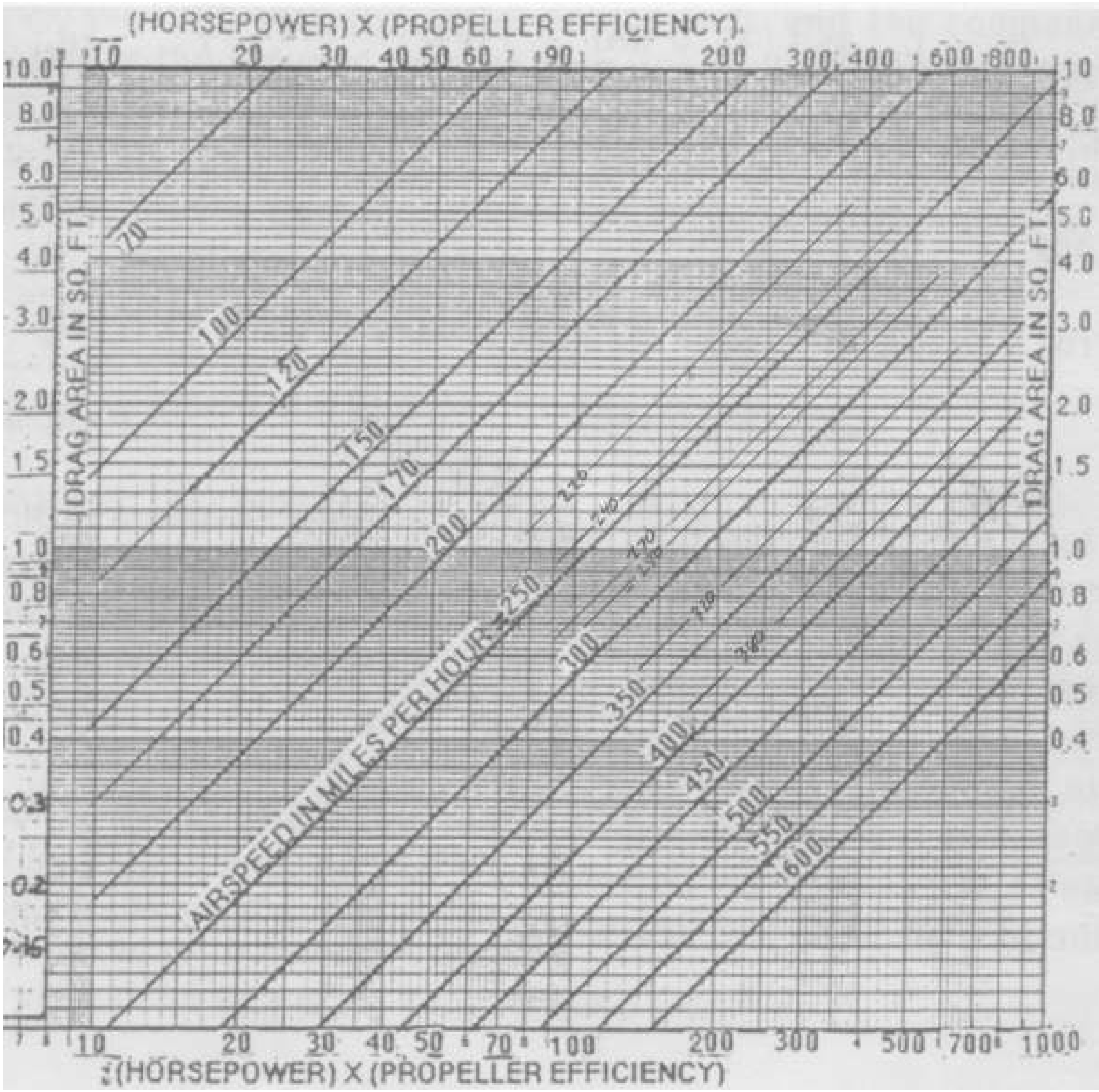
Fred Moreno January 2013

When it comes to bragging rights about who has the "slickest" airplane, we can settle the bet with some careful measurements and then calculate a number to decide who wins the bet. The number we want is called the **"simplified" flat plate drag area** which represents the area times the air flow impact pressure that yields the total drag of the airplane.   This gives us an easy comparison of various aircraft drag figures for the high speed cruise portion of the flight envelope. Here are some figures, most of which I dug up from Bruce Carmichael's book Personal Aircraft Drag Reduction (1995):

Aircraft	**Simplified Flat Plate Drag Area**
1950's era jet fighter, rough	4.0-5.0 square feet
Cessna 172/C182 class (they vary a lot – antennas etc.)	around 6
C-210/Beech Bonanza class (same comment)	around 4
Columbia/Cirrus Lancair ES	around 3
Voyager (remember, it flew very slowly)	5.4
A.J. Smith's AJ-2 (1980) 200 HP, 280 MPH top speed	1.14
Bellanca Skyrocket 1983	2.83
Lancair 200 (0-200 engine, calculated by Carmichael)	1.61
Mike Arnold's tiny AR 5 (213 mph on 65 HP)	0.88
Nemesis (formula 1)	0.6-0.72
Lancair ES	around 3
Lancair IV prototype (turbo, calculated by Martin Hollman)	2.12
VH-YFM, Fred Moreno's modified Lancair IV, non-turbo	~1.85-1.90

Flat plate drag area lumps ALL the drag – parasitic (friction), cooling, and induced from the generation of lift – into one number. To make a reasonable comparison one has to compare performance at the same operating regime, most usually maximum speed or a high cruise speed. Small errors in TAS measurement and power assumptions make large errors in flat plate drag area so the resulting number you calculate is always subject to a sizable error band. Making an accurate calculation requires calibrating instruments, very carefully controlled flight (autopilot on for precision altitude control) in smooth air as we shall discuss below.

NASA aerodynamicist and drag reduction expert Bruce Carmichael provides a neat graph in his book Personal Aircraft Drag Reduction (1995, published by the author) that allows one to estimate flat plate drag area. It is reproduced on the following page. It assumes you make a speed run at sea level, standard day, that you know the horsepower, and that you know the propeller efficiency.



How to Do It – The Most Accurate Way

If you can do a low pass over the ocean (or at sea level in Death Valley) on a 59F day with barometric pressure of 29.92 inches of mercury, do the following:

1. Make a full throttle blast two ways and average GPS readings of ground speed. Three or four ways is better yet. Be sure to let the airplane accelerate to final equilibrium speed which may take several minutes. If the barometric pressure is higher than standard, set standard in the altimeter window, climb until the altimeter shows sea level, and test there. If the barometric pressure is less than standard, do not descend below sea level! If you cannot get standard conditions you will have to correct for pressure and temperature (calculate density altitude).
2. Check manifold pressure and make sure it is adjusted to the engine manufacturer's manifold pressure for full power. If you are getting ram pressure benefit from your speed, correct power for the higher manifold pressure, or pull the throttle until you get the right manifold

pressure for 100% power. Don't just assume you are getting 100%. You may be getting more. Record data: GPS TAS, manifold pressure, temperature, density altitude if your EFIS displays it. For non-turbo engines, each extra inch of manifold pressure adds about 3% more power. If you are skimming the wave, have a friend record the data. You keep your eyes outside of the cockpit!

3. Go home and average all your air speed readings. Multiply your average TAS in knots by 1.15 to get TAS in miles per hour.
4. Assume 85% propeller efficiency. Multiply your actual horsepower (full power or corrected for differences in manifold pressure) by 0.85.
5. Go into the chart. Slide down the diagonal line for your HP times prop efficiency until it intersects the vertical line for your TAS in miles per hour. Remember: MPH = knots times 1.15.
6. At that intersection, go horizontal to left or right and read off the flat plate drag area on the vertical axis.

The Simple Way – less accurate

Most folks are far from the ocean making the sea level full power standard day blast difficult without tunnelling equipment. In that case it is necessary to do a test at altitude, and correct for altitude, temperature, aerodynamic heating and be careful for rising air (middle of a big low) or sinking air (middle of a big high). There is a simple way and harder ways that are more accurate.

For <u>constant power</u>, speed increases roughly 1% per thousand feet for the first 10,000 feet or so. So your procedure is as follows:

1) Pick a smooth air day and fly the four way box recording GPS speeds. Autopilot on, allow the airplane to reach equilibrium, record data. Make autopilot commanded gentle turns to the new direction, and allow two minutes (preferably more) after an autopilot gentle turn to establish equilibrium after the turn. Remember, we are going for super accuracy.
2) Record your engine data so you will be able to make a horsepower estimate. More below.
3) Record density altitude if your instrumentation permits, or record OAT and then calculate density altitude later on. You will later correct for aerodynamic heating of which more below. Some instruments like the Chelton EFIS do this automatically.
4) Go home, average all the readings.
5) Then correct for altitude by reducing your average calculated TAS by 1% per thousand feet of density altitude to get an estimate of the speed you would have gotten at sea level standard day.
6) Go into the chart. Slide down the diagonal line for your HP times prop efficiency until it intersects the vertical line for your corrected sea level TAS in miles per hour. Remember: MPH = knots times 1.15.
7) At that intersection, go horizontal to left or right and read off the flat plate drag area on the vertical axis.

Slightly More Accurate

There is a way to make this estimate slightly more accurate. Don't use the 1% rule above. Instead, go to the table below for the standard atmosphere, also from Carmichael's book.

Density Altitude, feet	Density Ratio	Air Density lbs/cu ft	Cube root of density ratio
0	1.0000	0.0765	1
1000	0.9711	0.0743	0.9903
2000	0.9428	0.0721	0.9806
3000	0.9151	0.0700	0.9709
4000	0.8881	0.0679	0.9613
5000	0.8617	0.0659	0.9516
6000	0.8359	0.0639	0.9421
7000	0.8106	0.0620	0.9325
8000	0.7860	0.0601	0.9229
9000	0.7620	0.0583	0.9135
10,000	0.7385	0.0565	0.9040
15,000	0.6292	0.0481	0.8570
20,000	0.5328	0.0408	0.8109
25,000	0.4481	0.0343	0.7654

Use the following procedure

1) Same as above
2) Same as above
3) Same as above
4) Go to the table above, to the Density Altitude column. Look down the column until you get to your density altitude.
5) Go horizontally to the right column, the cube root of the density ratio. You may have to interpolate. In other words, if the density altitude for your test was 8500 feet, then pick the average between 8000 and 9000 which are 0.9229 and 0.9135 Half way between these numbers would be 0.9182.
6) Multiply this number by your GPS TAS average from your test flight to get your equivalent speed at sea level.
7) Go into the chart. Slide down the diagonal line for your HP times prop efficiency until it intersects the vertical line for your TAS in miles per hour. Remember: MPH = knots times 1.15.
8) At that intersection, go horizontal to left or right and read off the flat plate drag area on the vertical axis.

Using your Calculator

If you don't like the chart, you can record data and use your calculator. The formula is shown below

DA =5231 HP/ (air density times velocity cubed)

Where

- DA = Drag Area, square feet

- Air Density is the air density at your density altitude, pounds per cubic feet, from the table above
- Velocity is TAS at altitude in knots
- 5231 is a constant that takes into account conversion of HP to foot lbs per second, the gravitational constant 32.2 ft lb mass/lb force seconds squared and ½. Math explained later.

Some Cautions

Because there are a lot of estimates in power and prop efficiency and potential errors in air speed measurement and temperature, it is hard to get flat plat area accuracy to better than 10%. Multiple flight tests are needed to confirm data and do some statistics, more than most of us are willing to do. Fanatic? Do three sets of test flights, same conditions (or as close as you can), average those results. The differences in TAS numbers from three sets of tests will give you a feel for the accuracy (or conversely, the size of the errors) in your measurements.

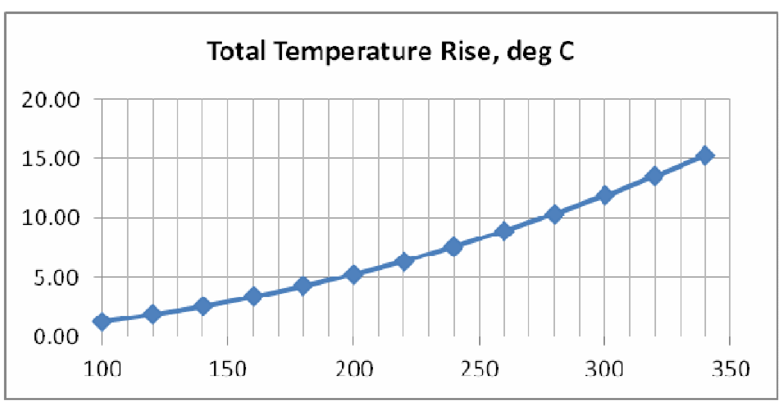
Be wary of single point test data. It is easy to get a data point that looks really good. But you will only be fooling yourself.

The Tricky Part – corrections and estimates

Outside Air Temperature (OAT)

If cruise speeds are high enough, there are aerodynamic heating effects that raise the temperature you read for OAT above the REAL OAT. As noted some EFIS systems (notably the Chelton) correct for these effects and present a "corrected" TAS number in that little box on the top left of the second screen. I don't know about other systems.

Temperature errors arise from both frictional/compressioneffects (about 2/3's of the error in OAT from an uncorrected instrument) and compressibility effects (about 1/3 of the total error). Making some reasonable assumptions one can arrive at a simple formula for the total temperature rise versus TAS which yields the curve shown in the figure below.



Total Temperature Rise vs. TAS in knots

So if you are using a simple OAT measurement instrument which is usual for most of our airplanes, you need to take your OAT measurement and then correct it (reduce it per the chart above) to get the actual OAT. Example: if your TAS is 200 knots and your measured OAT is

15C, then the corrected OAT is 15C – 5.0C = 10C. Use this number to calculate the density altitude when making your TAS corrections back to sea level.

Horsepower

Engines vary in their power output. For the Continental 550 series engines from the factory, the guarantee error band is that the power output is minus 0% and plus 5%. Other manufacturers use different error bands. ALL manufacturers base maximum HP on sea level ambient pressure (29.92 inches of Hg), 59F, and DRY AIR (no moisture). Real HP will be a trifle less with real world moisture, and of course higher temperatures will sap horsepower more. On a very hot 100% humid day, water vapour could be 4% of atmospheric density, and power suffers accordingly.

The only way I know to be reasonably sure about HP is to have a comprehensive engine power table for all altitudes and temperatures. For the IO-550 series, one can use the power tables for the Columbia/Cessna 350 or Cirrus R22. But even these require some interpolation.

For the IO-550 (stock) the following chart is useful.

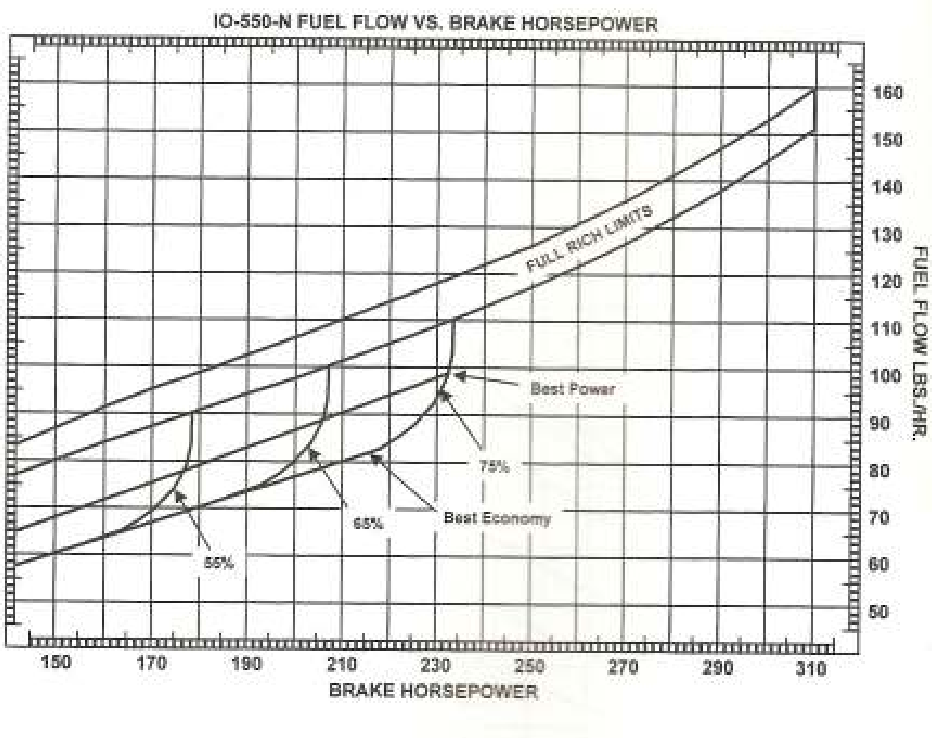
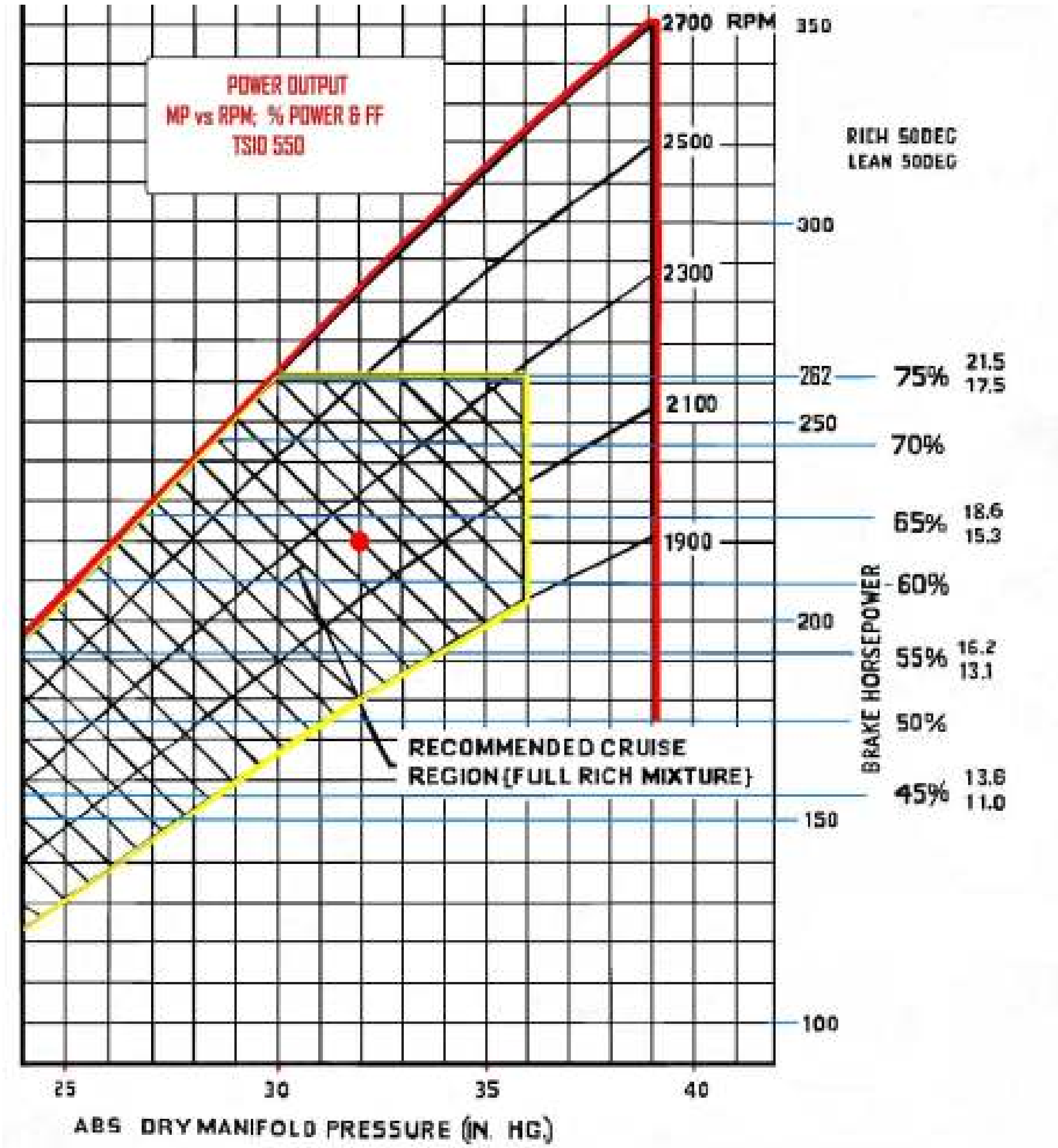


FIGURE 6-17. FUEL FLOW VS. OBSERVED BRAKE HORSEPOWER IO-550-N, P, R

The "best economy" line is for 50F lean of peak. To convert fuel flow in gallons per hour to pounds per hour in the graph multiply GPH by 5.85.

For the TSIO 550 the following chart is helpful.



The numbers down the right side beside the % HP numbers are the fuel flow in gallons per hour for 50F rich of peak and 50F lean of peak. I am not sure of the origin of this chart, but I believe it is the folks at GAMI or those who offer the engine operating courses (Walter Atkinson *et al*).

The other way to estimate engine HP with reasonable accuracy is to operate 50F lean of peak, measure fuel flow accurately, and then convert to horsepower knowing the compression ratio. Lean of peak ALL the fuel is being burned, so this method works. RICH of peak, all bets are off because some portion of the fuel is not being burned, but dumped out the exhaust in the form of lots of carbon monoxide and unburned hydrocarbons.

To calculate horsepower based on compression ratio, you need to know compression ratio which can give you a conversion factor for your engine.

- For the IO-550 engine operating 50F lean of peak, stock 8.5 compression, the fuel burn at 65% (201.5 HP) is about 14.9 horsepower per gallon per hour, a specific fuel consumption of 0.391 lbs/hr/hp.
- Raise the compression ratio to 10 and the figure becomes 15.6 horsepower per gallon per hour, specific fuel consumption of about 0.37 pounds per horsepower hour, an improvement of about 5%.
- For carbureted engines that cannot operate smoothly at these lean conditions, an estimate can be made using a specific fuel consumption of 0.42 pound per horsepower hour. So for a 180 HP Lycoming at 65% (117 HP) you would expect to be burning about 49 pounds per hour or about 8.4 gallons per hour to make this much horsepower.

So in your testing, if you are measuring fuel flow, you should be able to get a pretty good fix on the horsepower generated by the engine during your test flight. Multiply by 0.85 for the assumed prop efficiency (another source of possible error), and you get the net horsepower delivered to make thrust. Use this number to enter the chart and find your flat plate drag area.

Some Examples

Below I have summarized three sets of estimates for drag area with my plane, a non-Turbo Lancair IV with IO-550 engine and innumerable little mods to reduce drag.

Example 1 – Brand new with High Compression Pistons (10:1), best power

When new with engine barely broken in, nary a bug, nick, or speck of dust on the airplane, light weight, every seal in place – perfection - I recorded a maximum speed of 257 knots at 9900 feet density altitude. My power charts showed the engine was putting out about 84% power, or about 273 HP for my high compression IO-550. Assuming a prop efficiency of 0.85 yields a thrust power of 232 HP. At sea level, a rough estimate of sea level speed would be about 90% of the speed at 10,000 feet (a 10% adjustment for altitude change), or 231 knots or 267 MPH. Using the chart, the flat plate drag area would be roughly 1.8 square feet which probably turned out to be a bit optimistic due to errors and simplifications. Keep in mind that this includes all drag: induced and parasitic including cooling drag.

Example 2 – Full Power Sea Level Blast

During this event, the engine had been returned to stock 8.5:1 compression ratio, we had nearly full tanks and 420 pounds of pork in the front seats. We skimmed the ocean on a calm day across King George Sound. The airplane had about 150 hours on it and so was not pristine with some bugs, nicks, and the prop spinner seal gone. I forgot to record the altimeter setting, but the GPS and Chelton corrected TAS were in general agreement within a couple of knots. Manifold pressure was 32 inches due to ram pressure, and the engine monitor showed 106% power. Seeing that and recognizing that my maximum fuel flow was not rich enough for that power setting, I terminated as we were showing about 240 knots. Put that all together and you get about 1.9 square feet for flat plate drag area.

Example 3 – Typical Cross Country Cruise

In September a friend and I completed a 4500 NM trip weaving across Australia and back. The airplane had 250 hours on it, was somewhat a little buggy, dusty, and a bit worn with some seals missing, in other words, a typical cross country trip condition after a few years of thrashing around. Average cruise conditions were 65% power, 50F lean of peak, about 8000 feet density altitude, and we were usually heavy. Use the calculator approach and it yields 1.92 square feet. Clean and bug free would make a modest improvement. I know that lots of bugs cost about 10 knots compared to squeaky clean, a big effect on drag area because of premature boundary layer transition from laminar to turbulent on the front half of the wing area.

My conclusion: in the clean condition, every seal perfectly in place, all nicks off the leading edges and prop, the airplane drag area is probably around 1.85-1.90 square feet.

The Underlying Math and Physics

Remember that Drag = Thrust at equilibrium, level flight.
Net Power = Thrust times Velocity = Drag = ½ *drag coefficient*area * air density * velocity squared

But Net Power delivered to the air is engine power times prop efficiency, PE = 0.85 (estimate)
Also: ½ *air density* velocity squared = ram pressure, what the pitot tube senses,
And: drag coefficient times area = flat plate drag area, DA, what we seek to determine.

So we can solve for DA. To get the units to work out we need some conversion factors:

1 HP = 550 ft lbs/sec
1 knot = 1.6877 feet per second
Gravitational Constant = 32.2 ft lb force/lb mass second squared

So that $$DA = \frac{(HP)(550)(PE)(32.2)}{(1/2)(\text{Air density})(\text{Velocity in knots squared})}$$

So: DA = 5231 HP/(air density times velocity squared)