Sunset Engine Development

AEROMOTIVE

Part 2

What is an aircraft engine? A child might answer, "an engine that's on an aeroplane." Foolish youth! If we skip the radials, rotarys, sleeve valvers, two strokes, diesels, turbines, jets, and rockets, we're left with . . . the four cycle, internal combustion, spark ignited, piston reciprocating, poppet valvers, in only; aircooled, liquid cooled, inline, opposed, vee, naturally aspirated, and supercharged gasoline consuming variations. These qualifications squeeze the answer into a set of characteristics that appears remarkably like an automotive engine to enthusiastic people.

Back To The Basics: We can attempt to equate engine performance in a variety of ways. However, horsepower still seems to be the best method if it is qualified by an accompanying RPM (revolutions/minute). Power output in HP/CID (horsepower/cubic inch displacement) is a standard for most engine nerds but it doesn't reveal much about the drivability (torque) or personality (horsepower curve) of the engine. Torque and horsepower are intimately related even though they are often spoken of as if they were separate entities.

I have taught a private engine design and building course for 21 years and it has always been a challenge to get my students to understand the relationship between torque and horsepower. This doesn't surprise me because these two parameters, ostensibly simple, are in fact tricky to relate.

I am reluctant to rehash the whole horsepower/torque issue. But, based on conversations I have had with aircraft folks - and automotive folks, for that matter - I perceive the need to establish basic terms. We (“we” meaning us at Sunset Engine Development) are often asked, "what do I want, torque or horsepower?" Trying to explain such abstract concepts on the telephone cannot do the subject justice. While torque and horsepower are the two basic parameters of our business, they are a subject we have never written about before. As engine builders and teachers we can see where we can help ourselves by helping our customers to better understand these concepts.

We learned about the relationship (torque and horsepower) in a way which was easy to understand. Our first dynamometer was a manually controlled unit where the operator had to vary the load valve and the throttle at the same time to place engine RPM at the desired point. This is akin to patting your head and rubbing your stomach at the same time - but, one learns and gets good at it. The main instrument on the old dyno was the torque meter. A large dial, or gauge, that converted a hydraulic pressure from a load-cell to a analog number. In effect, it's just a big oil pressure gauge. With the engine running this gauge only measured force. After the engine was shut down the gauge number was translated to a torque number and this number was then multiplied by the observed RPM to derive the horsepower. With this type of dyno tests were generally started at the highest RPM point and the load was increased consecutively. Each time the load was increased the RPM would drop and the torque needle would swing higher until it reached a point where the engine couldn't run properly. With modern dynos the load is controlled automatically with a servo-valve and there is no torque meter. We get a horsepower and torque figure simultaneously on a digital screen, with only finger-tip work on our part. Because the process is now controlled by computers it is easy to loose the "feel" for the engine's power that we got with our old dyno.

It was Allen Freed who coined the term "rock and roll" and today its intrinsic meaning and roots seem to be as obscure (based on what I hear my son listening to on the radio) as James Watt's definition of horsepower.

Horsepower: According to James Watt, a horsepower is supposedly the power of one horse, and a measure of the **speed** at which a horse can work. It may seem strange that in this modern day we still compare the power of an engine with the speed at which a horse can work. However, years ago, when engines were new, some sort of measuring stick was needed to compare the power of different engines. Since the horse was then the most common source of power, it was natural that the power of engines should be compared to the power of horses, that is, as horsepower.

It was found that an average horse could raise a 200-pound weight a distance of 165 feet in 1 minute. Often the horse is pictured pulling a rope that passes over a wheel and lifts a basket of rocks vertically up a mine shaft. The horse has linear movement and the wheel is rotational. 165 ft X 200 lbs = 33,000 ft/lbs per minute. Therefore since the horse could do 33,000 foot-pounds of work in one minute this was defined as one horsepower. James Watt is the guy responsible for quantifying this.

One of the reference books that I use in my engine class had a interesting historical note on James Watt -

> The Scotsman, James Watt (1736 - 1819), was one of history's most prolific inventors and engineers. Although he didn't invent the steam engine, his improved engine with a separate condenser (which he patented in 1769) improved the engine's efficiency more than 70 percent. Watt also developed a furnace that consumed its own smoke (a leader in air pollution control) and an early copying machine. A little known fact is that he was the first scientist to prove that water is a compound of oxygen and hydrogen, not an element.
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> Remember that Watt worked out the calculations that gave us the horsepower as a standard unit of power measurement. His formula for computing horsepower was based on the fact that a horse could move 200 pounds 165 feet may seem like an odd unit of distance measurement, but was it? Watt started with a traditional English unit, the rod, which was used in surveying and mining engineering of his time. One rod equals 16.5 feet, and convenient distance measurement for his calculations was 10 rods, or 165 feet. Do you suppose he was thinking metric and actually invented a standard unit we could call "one dekarod?"

I have read elsewhere that Watt arbitrarily set up 33,000 ft/lbs. per minute as one horsepower, and actually, it was 50% over what a powerful horse could do. I, for one, don't believe that, it seems to me a horse could do as much, if not more work than, Mr. Watt's horse. In reality it doesn't matter what you believe, it's just a standard. Of course it's not a perfect standard, for instance it can't properly describe the thrust of a jet engine. The J-58 in the SR-71, probably the world's most powerful ram-jet engine, if running on a test stand (at zero forward speed - we hope) is developing zero horsepower.

Torque: Torque comes from the Latin word *torquer*e - to twist : a force that produces or tends to produce rotation or torsion. Torque is a twisting force and that is exactly what a crankshaft is doing to an axle or propeller. Force applied in a linear direction is expressed in ft/lbs (foot-pounds). A force applied in a rotational direction (like an reciprocating engine produces) is called torque and is properly expressed in lb/ft (pounds/feet). You can have torque without movement .

By definition, horsepower = torque x RPM divided by 5252. Therefore at any RPM above 5252 HP will always be greater than torque and at any RPM below 5252 torque will always be greater than HP. Transposing the formula around gives Torque X RPM = HP X 5252. Set RPM to 5252 and you have Torque = Horsepower @ 5252. In other words the curves always cross at this RPM. Who can say - if Watt had been a chicken farmer then the curves might not cross until 10,000 RPM. Another point to realize is that below 5252 RPM any increase in torque will be accompanied by a lesser increase in HP. For example, a torque increase of 2 lb/ft at 3000 RPM = 1.14 horsepower increase. The same torque increase at 10,000 RPM = 3.8 hp increase. You can shift the power and torque peak up and down the RPM scale as a function of displacement and the components selected, but, horsepower and torque will still always cross at 5252 RPM. Torque is a two component function - force (or weight) and a distance. Horsepower is a three component function - force, distance and time. You cannot have horsepower without time and torque.

So, where does this 5252 come from? To change a linear force to a rotational force we need to divide by 2 pi. Therefore; 33,000/6.2831853 = 5252.1131- according to my calculator.

On a humorous note, we discovered an interesting observation of horsepower that I never considered, deriving the RPM of a horse. If the wheel that the horse is lifting that 200 lb weight by has a one foot radius then its circumference is 6.28 feet. If the horse walked 165 feet then that pulley turned 26 times. Hence, the RPM of a horse is 26. Humm? Horses on the European continent must not be as strong because their DIN horsepower is based on 32,500 ft/lbs which yields a different HP number than the US equivalent. You can calculate metric horsepower from SAE horsepower by multiplying by 1.0139. To convert back multiply by .9863. We've included a chart at the end which shows the fixed relationship between horsepower, torque, and RPM.

When I was on the aircraft carrier USS Ranger I made a horsepower observation. They rated its horsepower at 100,000. They didn't give an RPM but I've stood beside a shaft alley and watched it turn at what I think was pretty-much WOT (wide open throttle) and I can't imagine it could be more than one revolution per second. After all, there are four props with four blades per prop and each "blade" is 25 feet long. This horsepower number sounds big until you calculate the torque. By setting the RPM to 60 in the above formula and transposing; Torque = 100,000 X 5252/ 60 = 8,753,333 lb/ft torque. Not bad. Even though this torque number is more impressive, they still rate it by horsepower. Does that seem fair to Mr. Torque? On the other hand, turbine engines, spin fast and have high HP, low torque, and it seems right that they should be rated by horsepower.

Anytime we increase cylinder pressure (more heat release) we will increase torque and also horsepower. Some believe torque to be a more meaningful term when attempting to equate performance in low RPM engines - but - **it is still work that gets the job done** and since you cannot produce work without movement - RPM in this case - horsepower is the measure of how much work can be done. If we say, "since piston aircraft engines operate at low RPM we are most concerned with enhancing the torque in their operating window," we are equally correct to say we are enhancing the horsepower. Whether we talk torque or horsepower, as long as we know the corresponding RPM, we can derive the other. And - since we know these curves cross at 5252 RPM we can extrapolate a curve which will be very close to reality. When they say "it's horsepower that wins races (whoops - I've said that) they should realize that they wouldn't have that power without torque. So these terms aren't just kissing cousins - they're married to each other.

When people say they are going to build a "high torque" engine, we could, with equal veracity, say they are going to build an engine that produces high horsepower at a low RPM. We apply this high horsepower/low RPM concept to white-water jet boat racing engines. We build a large displacement mid RPM (5500 - 6000) engine. This enhances reliability while producing high torque. We then choose an impeller which gives the needed boat speed. Aircraft engine building methodology is similar.

Torque and horsepower are pretty much meaningless without their corresponding RPM. Given peak torque and RPM , and peak HP and RPM, you can construct a graph which helps visualize the engine's characteristics.

Quantifying Stress: Mean piston speed (MPS - in feet per second) is an often used indication of the mechanical loading of an engine. Traditionally limits were set on MPS which were not to be exceeded in deference to reliability. A better indicator might be the peak piston acceleration. This function determines the G-loads on the reciprocating components and the ultimate tension load on the connecting rods, bearings and crankpin. The highest loading on the piston, rod, crank and bearings occur at TDC during overlap (end of exhaust stroke - when the piston is changing direction) when there is almost no pressure above the piston. This is the tension load. In a normally aspirated engine above 1000 RPM it is usually higher than the compression load, at 15 to 20 degrees after TDC, when cylinder pressure is highest. For instance, a 350 at WOT (wide open throttle) at 2500 RPM will have a tension load at TDC of 403 Gs, which (given a typical reciprocating weight) equals 915 pounds of pull on the lower half of the rod bearing. At that same RPM the compression load (at 384 lbs/ft torque) equals only 486 pounds of load on the upper half of the rod bearing. Increase the RPM to 3935 - which equals 1000 Gs - and the loads go to 2266 pounds tension and 1206 pounds compression. These tension loads will increase as the **cube** of the RPM. There aren't many people who realize this.

Allan Lockheed was a speaker at the 1995 ADVANCED ENGINE TECHNOLOGY CONFERENCE. During his presentation he said something that caught me by surprise. He said that G loads increase as the cube of the RPM. Until then I always thought that the loads increased as the square of the RPM. I couldn't find this cube function printed anywhere in my reference textbooks. I called him to get a confirmation of his statement. He said that the equations for connecting rod loading are very complex and you won't find the derivation for them in any textbooks because they are so ugly. In fact, he has only seen them twice. This cube function can be seen by plotting RPM vs G load from his engine modeling software. If anyone wants to argue with this please call Mr. Lockheed - not me. Incidentally, his father founded the Lockheed Aircraft Company and his Uncle Malcolm invented the hydraulic brake and his other Uncle, Victor, is Co-Founder of the SAE. Allan has degrees in Computer Science, Mathematics, and Engineering. He is an engine theorist extraordinaire. He has authored THE ENGINE EXPERT™ which is the most useful engine modeling software that we use. He has been a very good source for engine data for this paper and others.

So. . . when you double the RPM you increase the loads by a factor of **eight**. Therefore, tripling the RPM will increase the loads by a factor of 27! It's the Gs that are responsible for the stresses applied to the rotating and reciprocating parts. If we know the Gs and reciprocating weight we can calculate the load from the formula; G (32.164 ft/sec^2) x Reciprocating weight = Load.

Mean effective pressure (MEP - in pounds per sq. in.) is a good way to express the average value of the forces acting on the pistons, indicating thermal and mechanical loading and also the level of specific torque. MEP is commonly known as cylinder pressure.

There are more inclusive ways to evaluate engine performance than average piston speed or cylinder pressure. By using only one of these parameters you don't see the big picture. A couple of years ago I read a technical article on the Ferrari V12 Formula 1 engine. This article in RACE CAR ENGINEERING, used the product of MEP x MPS, and defined this product as "work per unit piston crown per unit time," so as to amalgamate the values for the engine's thermal and mechanical loading. RCE said the MEP x MPS is one of the best indicators of the worth of an engine. We don't know what they mean by "worth" but we believe this product is an indication of the level of stress on an engine. Aircraft piston engines are not high RPM racing powerplants but this MEP x MPS formula deserves a close look.

For example, with the short strokes used in F1 engines their MPS is impressive, but their peak piston accelerations are nothing short of incredible for an endurance engine. It's also nice not having to deal with valve springs (all modern F1 engines use pneumatic valve closure systems). At 16,200 RPM (which is what one turns the Formula One Ferrari in 1994) their pistons accelerations are comparable to a small block Chevrolet engine running over 11,000 RPM. The Ferrari does it for two hours at a time. For 1995 Formula One has down sized their engines to 3.0 liters. Now Ferrari is turning them little suckers 17,600 RPM. Not many people know how piston rings seal at these accelerations. Actually the V-12 Ferrari's do not have piston accelerations as high as the V-8 Cosworth's because the Cosworth stroke is longer.

An engine's peak piston acceleration is set by its crankshaft stroke and RPM. The crankshaft stroke has the main influence on the mean (average) piston speed (velocity) but the shape of the curve is also influenced by the rod length. It is popular to use the L/R ratio (rod length divided by stroke) as an indicator of how suited an engine will be for high RPM use. There is a trap here that you won't read about in the magazines. At least I never did. I will explain.

I built my first real race engine for my own car in 1968. The salesman at the crankshaft company where I ordered my crank said if I were to use a "tall deck" truck block (.400" taller than stock) that I could use longer rods and the engine would rev like it had a shorter stroke. Since I had just read about L/R ratios in HOT ROD I "knew" what he was talking about. I grabbed my slide-rule (before calculators) and did some quick arithmetic. Since the stock rod has a center-to-center distance of 6.135" and a 427 had a stroke of 3.76 that gave a L/R ratio of 1.63. I wanted to build a 454 but knew the longer 4" stroke would produce more piston speed and shorten engine life. It would mean I couldn't rev the engine as high. I figured if the rods (Carrillo H-beam) were made .400" longer (6.535") that would yield an L/R ratio of 1.63 - same as the 427. I could have my cake and eat it too - i.e. more displacement for more power and lower piston speed for higher RPM which also meant more power. How could a guy go wrong?

I won a lot of races with that combination. At Tektronix, eight years later, we were just learning to write simple programs in "Basic." We wrote a program to plot piston velocity and acceleration based on stroke, rod length and RPM. At first I though the program was wrong because it showed my 454 to have significantly more "peak" piston speed and acceleration that the 427 even though they had the same rod ratios. What gives? It was then that I realized that the formula for piston speed (Piston speed = 2sN/ 12 in/ft - in ft/min where s = stroke in inches and N = RPM) didn't even include rod length. So the light came on. It's the stroke which sets peak velocity and acceleration. The rod length affects the shape of the piston velocity curve and only has a minor effect on **where** the peak piston speed occurs. A classic case of outsmarting yourself. Oh brutal reality. Fortunately my naivety didn't hurt me and, as it turned out, I was right for the wrong reason in building a bigger engine because the high quality components I selected never gave me any problems.

Since it's piston acceleration that determines the "peak" stress and loads why not use "maximum" G-load instead of MPS? I believe that a better indicator of engine stress might be G's X MEP. These peak stress loads are what is put into a components "mechanical memory" and once you put it there you can't take it back (thermal and mechanical stress relieving may help some). The higher the peak stresses the shorter the component life. I've included a chart with both MEP x MPS and G's x MEP for selected reciprocating aero/auto engines.

Loads Vs TBO: There are several types of loads and stress which influence the life, performance and well-being of piston type, internal-combustion, four-stroke-cycle, liquid-cooled, poppet valve, spark ignition engines. These loads are both thermal and mechanical. Both deserve careful scrutiny when evaluating an engine for performance and durability.

The crankshaft receives its primary stresses in the form of bending and twisting loads. Bending and twisting is happening even when the engine is idling. The connecting rods see a more complex load pattern. Rods must absorb not only bending and twisting but compression and tension loads as well. These loads are the result of combustion pressure, inertia loads, and centrifugal loads. They do not add directly.

The loads put into the crankshaft and connecting rod by the piston acceleration in an high performance automotive style aircraft engine are insignificant when compared to some of the other components. I wouldn't hesitate to use the rods and crankshaft that we use in our race engines for 20,000 - 30,000 hours in a low RPM aircraft engine. I don't see why you would ever have to change them. We can't say that about the piston.

The piston sees combinations of these loads in different sections of its structure, but, since it is also the bottom part of the combustion chamber, it has the added problem of having to withstand tremendous heat. That wouldn't be a problem if it weren't made of aluminum. Aluminum has a melting temperature very near the mean combustion temperature.

Materials get softer and weaker as they get hotter. The hotter the piston runs the softer and bigger it becomes and the more it deflects. This deflection in the pistons skirts, crown and pin-bosses conjures up the ole coat-hanger analogy that says you can only bend it back and forth so many times, depending on how far and how often you bend it, before it breaks. Everything in an engine has a finite fatigue life. Because of its material and the added thermal loads I label the piston as being the weak-link in the bottom end.

As we look at some of the TBO's (time between overhaul) that other engine builders claim for their conversion powerplants it becomes apparent that we worry more about pistons than many other folks do. Over the years we have used pistons from almost every manufacturer with mixed results. The piston picture is clearer to us than it used to be. Perhaps this is because of our past experiences with "Hollywood" pistons.

In twenty-eight years of building engines a person has time to make many observations. My piston observations have been interesting. I used TRW pistons in my first few race engines and never had any problems. Then I started building engines which required non-stock CD's (compression distance, from center of pin to deck of piston) and for these I had to buy custom built pistons. Over the next fifteen or so years I used pistons from every manufacturer. Most of these are in California. Saying that most of these piston suppliers are manufacturers is almost a misnomer since most of them they buy their forgings from Alcoa. They only whittle on these forgings. The Alcoa forgings only come in two flavors; 2618 (low-silicon) and 4032 (high-silicon) alloys.

For a bit of historical interest, perhaps the best alloy ever developed for a piston was done by Rolls-Royce. Circa WWII Rolls- Royce went to extreme lengths to procure the very best material for its piston. The alloy they chose was designated RR-58. It was a special alloy designed for their supercharged Merlin V12 engine which powered the Spitfire and Hurricane fighter aircraft. These pistons were also used in the P-51 Mustang and what was one of the most powerful aircraft piston engines ever produced, the H-24 Napier Sabre engine. In combat-ready form the H-24 produced 5500 HP.

Cosworth has earned a enviable reputation for reliability and uses this RR-58 in their racing engines. Their involvement in racing goes back many years. They have 13 Formula One world championships including 1994. Cosworth also uses this alloy in their high performance engines.

The RR-58 alloy is different from anything that had been produced for a normal automotive piston. Cosworth makes pistons in this material for the small-block Chevrolet but unfortunately only in limited versions for the big-block. Cosworth builds Chevrolet racing pistons designed the way they want them and to protect themselves and the customer you can't get them any other way. Most other piston manufacturers will build you anything you want whether it will work or not. There are obvious pros and cons to both philosophies. We have used Cosworth pistons in some of our big-block Chevrolet white-water endurance engines. I thought the cylinder-walls and skirts looked better than I had seen with any other piston.

Unfortunately, Cosworth rarely has all the features we are looking for in pistons. Lately, I start to wonder if this is a positive rather than a negative because it could be a way of protecting ourselves from incorporating design features (like bizarre ring combinations) that don't work. Cosworth obviously knows this.

There is now a custom piston manufacturer declaring that they are building pistons from a similar alloy. JE claims they have an aircraft alloy. When I ask them if it's RR-58 or similar the salesmen suddenly become very vague. They won't or can't even tell me why they refer to it as an aircraft alloy. Even though the material sounds suspiciously like hype, in reality, it works great. We have used it in some big turbocharged endurance engines and in some small sprint stuff and the results have been impressive. The material does seem different and they clearly aren't the dreaded Alcoa forgings. Maybe they had a Cosworth piston analyzed and were able to brew one with similar material characteristics? Lean cylinders are a leading cause of piston failures. Over the years we have tried everything out there and these seem to be the most forgiving of excessively lean fuel mixtures. These are the pistons we prefer to use.

A few years ago a new piston emerged called Hypereutectic. These cast pistons are purported to have some of the forged piston benefits. In case you're interested, "eutectic" has to do with the maximum amount of silicon that will remain dissolved in aluminum as the metal cools. The break occurs at 12% silicon content. Alloys with less than 12% silicon are called "hypoeutectic," while those with more than 12% are called "hypereutectic." The amount of silicon in an alloy affects the hardness of the metal, its ductility, and thermal expansion rate. Most forged pistons range from 10 to 14% while the hypereutectic ranges from 16 to 22%. While these pistons do most everything better than the normal F-132 cast pistons used by car companies they are by no means as strong as a forged piston made of 4032, 2618, VMS-75 (exclusive to TRW) or RR-58 alloy. Their higher silicon content makes them too brittle for most high output applications. They can shatter. Manufacturers may argue this but you're not going to get any experienced engine builder to use them in a race engine. We draw the line at about 420 lbs/ft (180 psi MEP) torque with a 4" bore. They are what you get in the ZZ3 and are fine for this engine as long as you keep it normally aspirated and don't ask it to run at high RPMs.

I'm not saying "be scared of your pistons." Pistons are not a problem unless they are abused. Yet, I do think that the pistons and rings are the shortest lived components in the bottom end. Any component that can go over 200,000 miles in a production automobile can't be labeled unreliable. But - production automobiles are not run steadily at 3500 to 4500 RPM at or near their peak torque as are aircraft conversion engines. So what am I trying to say, you ask? Well, it's that you can't expect the same longevity from a piston when used in an aircraft engine.

We have noticed another interesting quirk in the TBO issue. Most aircraft people are aware of the Thunder Engine project. Thunder is attempting to get FAA certification for a 495 cu. in. turbocharged Chevrolet BB based engine. Thunder rated their engines at 700 HP at 4400 RPM at 52 in/hg ABS. They call this the maximum continuous use setting. The technical paper I read didn't mention torque but by plugging numbers into the formulas I can interpolate the torque curve. To make 700 HP at 4400 RPM they would be producing approximately 840 lb/ft torque. That equates to a mean cylinder pressure of 256 psi. An aggressive number for any engine. My computer model says at 4000 RPM they would be making 900 lb/ft and an MEP of 273 psi. The AIAA paper reports a MEP of 254 psi. That is serious cylinder pressure. At that MEP a 350 inch engine with a 4 inch bore would be making 680 lb/ft torque. It would have to be turbocharged and it would take the best race quality parts to survive, and it wouldn't have a long life - certainly less than a 50 hour TBO. A big-block (BB), however is a different kettle of fish. We have made steady-state pulls, on the dyno, with a turbocharged intercooled 550 inch BB at 1200 lb/ft torque. This was 323 psi MEP without sign of distress (on 100LL Av-gas by the way).

A lot of effort and money (I heard 16 million) has been expended on the Thunder engine project. From the papers I read I am impressed with their thoroughness and ability to solve engine related problems. These were obviously smart (unrealistic maybe) people. They were attempting to rate this engine at a 2000 hr TBO.

My own experience, forces me to conclude that 2000 hours, at those cylinder pressures, is extremely ambitious, if not unrealistic. Even at their 70% power rating of 3600 RPM that equates to 217 psi (realize that it is heat which produces these pressures - the higher the heat the more the pressure - Charles' law) this is equivalent to a 350 producing 510 lb/ft torque.

In the Thunder AIAA paper they listed ten different types of aircraft engines and their respective MEPs. The average was 290 psi. Very high for an aircraft engine. What they failed to mention was the recommended TBO intervals of these engines. The few engines I did recognize on their chart, were for combat aircraft. I'm no airplane expert but I think it's safe to say that in wartime, performance overshadows TBO. Even if the MEP is very high, the MEP x MPS, for these aero engines, is most likely less than that of the Thunder engine.

Perhaps I am too conservative with my TBO estimations to suit some people. My experience is mostly based on race conditions where thermal and mechanical loads are high. Professional race teams change pistons after every race. If they believed there were no possibility of them failing they would use them for two races.

A customer of ours, Blaine Trent, put a different spin on the TBO issue for us awhile back. He said these FEW P-51s (Fighter Escort Wings P-51) are, after all, recreational aircraft. The owners will be lucky to be able to put 100 hours per year on them. At a 1000 hr TBO, that's ten years between overhauls. Based on that point of view should I be less concerned with the TBO interval?

Fuel Injection: There are two types of fuel injection, mechanical and electronic. With mechanical you get constant flow or timed (sequential). In electronic systems you can get constant flow (batch fire), simultaneous double fire or sequential. The systems that tell these injectors when and how to open fall into three categories: mass flow, speed density and alpha-N. These systems may or may not have a sub-system to operate in a "closed loop" mode when strategies allow this. Both mechanical and E.F.I. (electronic fuel injection) systems range from the simple to the complicated. Once you understand the basic operating principals, as with anything, they becomes less intimidating and more attractive.

Since their introduction electronic fuel-injection systems have proven themselves millions of times under the harsh conditions of everyday driving. The on-going development of the control systems and sensors has allowed these systems to become more precise and reliable. Their sophistication has led to more efficient, economical, more powerful, and lower polluting engines.

We are comfortable with the Airflow Performance constant flow mechanical fuel injection. This is a Bendix derivative and the manufacturer affirms that it is mass air sensing. That makes it a natural for aircraft. Like any constant flow system it requires a certain technique for starting and stopping the engine. This should be "no big deal." These systems are easy to tune on the dyno because there is only, fuel pressure, a main jet and the individual nozzle sizes to worry about. The manufacturer does a good job with the base calibration. This makes it easier for us and requires much less dyno time than would be the case with an E.F.I. system. Cost-wise this system is about what a moderate E.F.I. system would cost and less than 1/3 of the EFI Technologies system.

There is no doubt that the engine will work fine with the Airflow Performance mechanical system, but we feel we would be remiss if we didn't inform our customers of all the options available. If we didn't sooner or later someone would wonder why we didn't use E.F.I. on their engine. Like the Airflow Performance system an E.F.I. unit can also sense altitude and adjust the fuel mixture accordingly. There are things, however, that E.F.I. systems can do that a mechanical system cannot. These are the things we feel people need to know about.

E.F.I. is the best type of engine management system, especially when combined with electronic spark control (ESC). External sensors qualify how a Central Processing Unit (CPU) follows strategy "maps." These maps can get quite complex looking and take many dyno hours to construct. I have included a comparison of a E.F.I. spark map to two types of mechanical distributors. Fuel and spark can also be made to work in the closed loop mode. In case you're not familiar with the term "closed-loop," the thermostat in your house operates closed-loop because it keeps the house within a preset temperature range. The most popular type of closed-loop fuel control does this by sensing unused oxygen (O2) in the exhaust. Depending on the voltage the CPU receives from this O2 sensor, it may override the map to keep the air-fuel mixture in the strategy range. Electronic spark control adjusts the spark timing based on a map similar to the fuel map. The engine may require a different advance at every different manifold pressure and RPM point. In theory, any change in fuel mixture should require a change in spark timing if maximum benefit is to be maintained from the combustion process. However, at one or more of these points (called break points - the EFI Technologies system, for instance, has 20 break-points for manifold pressure and 20 for RPM meaning that we must tune the engine at 400 different locations to complete the map) conditions may change to cause detonation. When detonation is sensed (via knock sensors mounted in the block) the spark is retarded a few degrees until the knock goes away. After a short time the timing is allowed to advance unless knock occurs again. Hence, closed-loop spark control. Engines, however similar they appear, can have different spark and/or fuel requirements at any given break point.

One real beauty of the EFI Technologies system and some others, is the ability to individually trim (adjust) the fuel and spark to each cylinder. We are about to purchase equipment that will give us the capability to do "in-cylinder" pressure measurement. This will enable us to record (on a digitizing storage oscilloscope) peak and mean cylinder pressures. We will be able to record crank-angle pressure and pressure-volume (pv) diagrams. We will be able to study fuel burn rates, detonation and cycle-to-cycle variability on an individual cylinder basis. This data should allow us to more accurately calibrate the spark and air-fuel mixture and determine how far the engine is from the knock limit. This will allow us to extract maximum efficiency (lowest brake specific fuel consumption) from the engine and yet remain safe from detonation.

I will explain further. Without this individual trim feature the picture isn’t as rosy. No engine’s cylinders receive an equal mixture of air and combustible fuel - especially at part-throttle conditions - even with port fuel injection. Because of this inequality in air/fuel ratio some cylinders will be leaner than others. It’s these lean cylinders or cylinder which establish the knock limit of the engine (it only takes one detonating cylinder to ruin the engine). Therefore fuel is added until the weak hole becomes safe regardless of the now enriched the others become. We determine the overall air/fuel ratio by monitoring O2 sensors, knock meters, air/fuel ratio, brake specific fuel consumption data while observing spark plugs and piston tops. Armed with this data and experience the tuner can achieve a fairly accurate fuel curve and rest assured that the engine is not going to have a detonation problem. However, with the ability to trim the amount of fuel in each cylinder and when you set fire to it (spark advance), as you can do with some EFI systems, changes the picture. Now there should be no weak cylinders and the engine should produce maximum torque, efficiency and reliability. Using an O^2 sensor in each primary exhaust tube is the only way this individual cylinder tuning can be accomplished safely.

We have dynoed engines over the years with various types of E.F.I. As with things electronic - computers and TV sets -the newer it is the better and trickier it is. They keep getting more reliable, smarter and in some cases less expensive. For instance, the new EFI Technologies system now has an internal data logger. I think data acquisition is good in an environment where the operator doesn't have sufficient time to monitor a lot of instruments. It also has a port which will communicate with a digital dashboard like those used in race cars. These could probably be adapted to work in an aircraft. Not only does it have closed-loop fuel and spark but closed-loop boost control (electronic controlled wastegate for supercharged applications) as well. It also has internal diagnostics that can display 128 different error codes.

Some people want to convert the Chevrolet LT-1 engine for aircraft use. Initially, we had a problem with this concept because we figured the factory OEM (original equipment manufacturer) E.F.I. units wouldn't lend themselves to a redundant ignition like some of the aftermarket systems. Al Hyde informs us that this is the route he is pursuing for his FEW P-51. He has a fuel injection guy who can put two of the ECU's (electronic control units) in parallel and therefore have redundant electronics for fuel and spark. This would allow an extremely smart injection system to have redundancy. It would cost about one third as much as the EFI Technologies system. It wouldn't have all the whistles and bells but unless turbocharging is required the owner probably wouldn't be able to tell the difference in performance over the very expensive EFI Technologies system. If this redundancy is indeed possible, the OEM tuned port electronic fuel injection, which first started coming on cars ten years ago, would be a good choice for a dependable fuel system.

With EFI Technologies the systems can be made redundant. We can add a complete but separate system to back up the primary. By the way, if safety is so important, why don't all aircraft use backup fuel systems? Just because something is mechanical doesn't mean it can't fail. Rodney Dodd - aircraft nerd, formerly of FEW, had a perspective on the reliability issue and used a term that fit so perfectly that I have adopted it also. He said it's a "confidence level." How much confidence do you require? The comfort threshold (for minimum confidence) is going to be different for everyone. That's why you can buy insurance premiums in different amounts.

If maximum performance or turbocharging is a design requirement then the EFI Technologies system is almost a necessity. I wouldn't want to see it done any other way. Even though it's more expensive and it would take us at least an extra week or two on the dyno to get the mapping tweaked just right, it is the smart way to go. I have included a list of features for this system.

There will be a kit purchaser - maybe more than one - who wants the aircraft to look authentic from the outside but wants it to have the latest technology inside. I know some people like this who have classic cars. The street-rod market now-days is full of people just like this. They want it to look like a 1934 Ford from the outside, but on the inside they want air-conditioning, cruise control, a CD player and under the hood they have 502 cubic inches, aluminum heads and electronic fuel injection. That's a typical street-rod now-days. There are some, though, who want to keep the car the way it was, with the stock interior and engine. It's the guy with the street-rodder mentality that is going to want the E.F.I. and other goodies that will make the aircraft "trick," (state of the art) different, (one of a kind) and faster than the next guys. The custom, “one-off,” work we have done in the past prepares us for this kind of customer.

OIL SYSTEM: The ZZ3 has a wet sump automotive oil system with the sump at the flywheel end. The engine would sit in the aircraft with this pan tilted the wrong way when on the ground and tilted the wrong way even more during climb-out. Because of this, it seems quite likely that, oil pressure fluctuations would be encountered and perhaps also during periods of turbulence. However, we don't know this for sure. We can't predict what forces may be encountered during flight. This is outside our domain of experience. We can say, though, that with a dry sump system there would be no condition, outside of an upside down negative G situation, where the outlet in the dry-sump tank would become uncovered. It is therefore the most reliable system, especially from a confidence perspective. The FEW P-51 is considered a high performance aircraft. It deserves a high performance oil system.

An added benefit to the dry-sump system is the ability to achieve negative crank-case pressure to provide an oil free combustion process. Crankcase depression combined with Av-gas should make the combustion chambers and piston tops appear almost as though it were running on propane.

The drawbacks to the dry-sump system are that it eats up space, weights more and is more expensive. Rodney liked the idea of mounting the oil tank behind the cockpit. This means oil lines would pass through the cockpit. Some people might not like this, but remember these are Aeroquip stainless-steel braided hoses. All racing sanctioning bodies say that there shall be no unshielded hoses passing through the driver compartment. They do consider this Aeroquip hose to be shielded and therefore allow it. If it is assembled correctly it is as reliable as anything can be made. Remember that the lines to and from the dry-sump tank are not under any pressure. If hose still bothers you, fittings can be welded to a length of aluminum tubing and the tubing can pass through the cockpit. If that bothers you then perhaps your confidence levels are out of proportion?

If you don't think you will get into a situation that warrants the expense of a dry-sump but there is still concern for flickering oil pressure during climb-out then an "accusump" system could be enough to put your confidence level over the hump. This is a pressurized oil accumulator which will cover-up temporary losses of oil pressure due to confused oil. Another alternative would be to build a special oil pan with the sump at the other end. Rodney suggested a center sumped pan to handle the nose down condition also. The problem is that these custom built pans are sometimes even more expensive than a dry sump pan. Since the pan is one of the major expense items in a dry-sump system why not just go all the way as there is no guarantee that any wet-sump system will work as well as a dry-sump.

Ken Melvin, another FEW customer, lives just a mile from us. Ken flew P-51s for the New Zealand Air Force (there can't be many out there who have flown the real McCoy) and has been a great source of information. In one of my first conversations with him he mentioned that the real aircraft was only rated for a few seconds at negative G's. In my naivety I said that seemed odd because you always see them inverted in dog-fight footage and such. His answer made it instantly obvious that you can be upside down and still have positive G's. Which isn't so obvious to those of us who don't get upside down on purpose. If flying along straight, level and upside down is a requirement then you are going to need an oil system designed for this. If you just want to do an occasional roll then the normal dry sump system should handle this. The point I'm trying to make is that just because you have a dry-sump oil system doesn't imply that you can fly inverted. I bring this up because this recently became a point of miscommunication with a customer. A lot of parts in the oil system need to be different for negative G operation. The oil pan, the oil pump, valve covers and the holding tank. Two additional components are required, a check valve and a breather tank with an internal check valve.

Rodney And Mike: Rodney Dodd and Mike Quigley came to see us awhile back. Not only are these guys genuinely nice folks but their knowledge of aircraft, engines and related systems is impressive. Rodney is now assisting FEW on a consulting basis only. In the near future he plans to offer his services to assist kit purchasers with the firewall forward installation of the engines, gear-reduction, prop and the plumbing. I think this would help those who can assemble the kit but perhaps lack the necessary expertise in the other areas

Trailer: We have built a trailer for George Bertwell which enables him to run his engine out of the aircraft. With the gear-reduction and prop he can chain it down and put load on it. By the time he gets his aircraft done he should have logged a lot of hours and be very familiar with the engine and its required techniques.

ZZ3 History: We offer the HO (high output) 350 product code ZZ3 as our base or "entry level" engine, if you will. It has been produced in three different version under three different part numbers since 1989. You can tell what you have by looking at the pad above the water pump. The three versions were stamped "ZZZ", "ZZ2" and "ZZ3" respectively. In my opinion, since Chevrolet has once again changed the engine, there have been four changes.

The first change - the ZZ2 - was primarily to the pistons. They went to an offset wristpin to achieve quieter operation when the engine was cold. It retained the ZZZ camshaft which was basically the old 350 horse 327 cam. It was just a flat tappet profile ground on a roller stick. The low-end performance wasn't very good because of excessive overlap.

In the next version GM went to a lower profile intake manifold and changed the camshaft. The original cam was a single pattern symmetrical unit with 235 degrees duration (at .050" checking Clearance) and .480" lift at the valve on both intake and exhaust. Since I'm on the subject of the ZZ3 cam I should regress and introduce Chuck Maguire. He does camshaft analysis for us and has been a great source of information on the ZZ3.

In November 1994 we had the opportunity to go to the first and perhaps the last "Engine Building Workshop" put on by Katech Engine Building & Development in the suburbs of Detroit. Katech builds engines for many successful racing teams, most noticeable for Scott Sharp who won the 1993 Trans-Am championship. They are the "General’s" (General Motors) race engine builder. The chute from the "big-house," as Fritz (Fritz Kayl; president) calls it, runs directly to Katech. I don't understand the exact reason for this workshop but it appeared as though Chevrolet Engineering wanted to get more technology into the hands of other engine builders who can make their company look good and sell cars. This was an incredible opportunity to learn state-of-the-black-art engine building theories and techniques. They had several heavy-duty speakers who talked about the things that we as engine builders want to know. For three days we were able to ask any questions and get candid answers. Since there were only 50 people in attendance, the one-on-one opportunities with these people were easy and actually encouraged. One of the speakers, Chuck Maguire, is a Chevrolet engineer who is responsible for most Chevrolet V8 and V6 roller camshafts designs. He has been working full time with engine simulation codes and valvetrain analysis since 1985 and has performed all of the performance analysis for the LT-1 V8 and L-35 V6 engine programs. Chuck's talk was enlightening and afterwards I asked him if he was familiar with the cam in the ZZ3. He said that he should be because he designed it. He was also one of the speakers at this years ADVANCED ENGINE TECHNOLOGY CONFERENCE in Colorado Springs.

What Chuck did was to design a dual pattern cam with 208 and 221 degrees of duration for intake and exhaust with .474 and .510 lift at the valve. He replaced the single-pattern symmetrical cam with a dual-pattern asymmetrical one. This is actually a inverted flank (hollow flank or secant flank) or a reentrant cam, as Chuck calls them, ground on a 36" wheel instead of a 12" wheel. So it is not reentrant in the true sense - you certainly can't see the dished out or undercut characteristic like on one ground with the smaller grinding wheels. He added exhaust lift and reduced the duration to get the overlap down. What that did, at least on dyno, was to keep the peak torque and power numbers about the same (as the ZZ2 cam). In the real world it brought the manifold vacuum up, made it idle better and greatly improved drivability below the torque peak, especially in an automatic equipped car. Performance was not lost. He said the only complaints he heard were from the people who used nitrous oxide. So who cares? Everybody is somebody else's weirdo. I recently called Chuck seeking his insight on some of the strange things we've encountered in the ZZ3s.

In the last engine we got things were different again. We noticed there was a different valve spring retainer and different valve seals. GM has gone to a different valve seat which blends into the bowl better. They have also added a windage tray under the crankshaft which doesn't mean much to us because our dry-sump pans have a built-in tray. They have also changed the timing chain. It is now a single row roller type chain which appears more robust than the last one. All of these changes should be improvements.

Another change is the connecting rod. GM has gone to a powdered metal rod instead of the forged "pink" which had been used in their high performance engines for about twenty years. We can't say for sure that this change was a definite improvement - yet. Maybe it's just the term "powdered", that bothers us. It doesn't seem synonymous with high strength. We're used to hearing terms like forged, billet, steel and such, to signify toughness and reliability. Powdered metal has been around awhile and is the trick way to solve problems with weight, material mass, and accuracy. Formula One cars have been using some of this technology in the brake department. But connecting rods? I don't know if these are stronger or even as strong as the old proven "pink rods" they replaced. When a magazine article says they are better they don't say how they are better. Better for the General's profit margin, or better for the end-user? But, for better or worse, we're stuck with them in the ZZ3.

Here's another thing which we consider to be a "problem". The cam bearings are honed in the ZZ3. Honing is a material removing process which can improve finish and change shape. The cam bearings in the ZZ3 are honed **after** installation. This is to align the cam tunnel. I'm not optimistic enough to believe that 100% of this material is washed away. The cam bearings have a hole which comes from the main oil feed line that supplies oil to the main bearings. Some of this honed off stuff should end up in that oil line. We, therefore, change the cam bearings so we can inspect and clean the grooves which surround each cam bearing.

This engine is still a great buy for the money. Unfortunately, by the time we're through investing a lot of time and expertise on it the price is much higher. If we were ever to divide the hours we put into this engine into what we charge, it would probably be under our normal shop hourly rate. To help you better understand the expense I will explain what we do to the ZZ3.

What We Do:

- ZZ3 is purchased new.
- Completely disassemble the engine. Inspect all parts for defects, assembly and clearance problems. Checking and changing clearances in an engine is time consuming and tedious work. It may mean that we have to change bearings. When checking bearing and pin clearances we use only dial-bore gauges - no plasti-gauge or snap gauges.
- Rehone block with the soft-hone method to produce a more desirable cylinder wall finish.
- Enlarge (one passage only), deburr and radius internal oil passages. Inspect and remove casting flaws from the block and heads.
- There is an oil groove behind the cam bearings that cannot be inspected without removing them. Bearing removal allows the grooves to be cleaned but also allows us to inspect them for core shift which can cause them to be restrictive to main bearing oil flow. When we install the new cam bearings we orient the position of the oil holes to minimize oil leakage from them. Incidentally, we know of a new Ford engine in which the oil holes to the main bearings were incompletely drilled. This resulted in catastrophic failure, but amazingly, only after the engine had run hard for some time.
- Replace freeze plugs with brass ones and epoxy them into the block with Devcon titanium putty.
- Paint certain unmachined areas of block.
- Deck block to zero deck height - this greatly improves combustion efficiency.
- Optimize cam timing.
- Accurately establish TDC. This may require us to build a different timing pointer.
- Re-shim valve springs.
- Modify combustion chambers and valve bowls to enhance air flow and combustion. This isn't critical but since the heads are apart anyway the effort is worth the gain.
- Mill intake manifold flanges for optimum port alignment with cylinder heads. This is a necessary operation when using an uncut manifold with a block that has been decked.
- Paint outside with heat resistant paint.
- Change hardware to special bolts and washers where warranted. We use aircraft bolts and ARP stainless hardware which has a tensile strength of 120,000 psi (Grade 8 is 110,000). We drill all bolts for safety wire.
- Pin and safety wire hardware as necessary.
- Degree damper (in milling machine with dividing head) for ease of leak-down testing and valve adjustment.
- Add dry-sump oil system and other auxiliaries.

After this work has been done the engine will be reassembled and dynamometer tested. Our goal is to test it with as many of the engine related systems and components as possible. This means tested with your ignition system, oil system and cooling system. With the alternator, brackets, belts, exhaust system, coolers and thermostats that you will use. We want to make this as much of a turn-key package as possible so that when it comes time to taxi surprises won't come from the engine compartment.

While on the dyno we will:

- Perform a controlled load break-in schedule.
- Optimize fuel and spark at the critical RPM/manifold pressure points, using 100LL Av-gas, to assure the engine is a safe distance from the knock threshold.
- Verify adequate oil and coolant flow.
- Optimize the valve adjustment.
- Retorque cylinder heads, intake manifold and other components until they are stabilized from heat cycling.
- Fix any coolant or oil leaks.
- Monitor engine wear with the screen oil filter and inspect the cylinder walls and pistons tops with a boroscope. We monitor ring and valve seal with leak-down tests and by observing blow-by cfm. Before the engine is removed from the dyno we give it a final leak-down and compression check.
- We will provide you with dyno sheets, horsepower and torque curves, final leak-down and compression figures. We will provide a recommended maintenance schedule and instruction manual. If any special tools will be required to service the engine we can provide an optional "tool kit."

After the engine is removed from the dyno we will:

- Remove the pan to inspect the bearings, camshaft lobes and give it a visual check over.
- We will clean the break-in lubricants from the oil pan.
- We then give things a final torque and Loctite or safety-wire all hardware.

When you install the engine all that will be required is to add fluids.

We like the idea of not removing the Airflow Performance throttle-body from the plenum and remote mounting it. However this requires additional expense. This cannot be done and use the stock water outlet location at the center of the intake manifold because the throttle-body would run into it. We mill off the housing which normally holds the thermostat and machine two aluminum blocks which bolt over the water ports (O-ring sealed) at the outlet end of the heads. From these housings we run -16 Aeroquip hoses which exhausts the water to the radiator or remote mounted thermostat - whichever the case may be. We also run a 3/8" stainless line from the rear of the heads to these outlet housings (see pictures). This is to keep water circulation high in an area where it is usually sluggish to prevent formation of steam pockets and to purge air from the system.

ZZ3 Observations: We are currently building engines for two people who have purchased the FEW P-51. They have both chosen our base engine package - the ZZ3. Both, also, have chosen the Airflow Performance fuel injection and a dry sump system (but not an inverted system). These two engines are, in essence, the same and it's nice being able to build two engines the same way. That rarely happens to us. However the engines are not identical because the General is continually making component changes to the ZZ3.

We took both engines apart and checked every component and clearance. We found some disturbing things to say the least. On one engine the main bearing clearances were too tight. Less than .001" vertical clearance on two bearings. In a car used for everyday driving this might never have caused a problem but in a high performance application it's playing Russian Roulette. Any clearance less than .001" anywhere in any high performance engine is to be avoided. Rodney Dodd related a story where they failed (bearing failure) a ZZ3 from a mild over-rev that actually shouldn't have hurt it. He contributed the failure to inadequate bearing clearance. After my observation of this engine I would have to agree with him. I just didn't think Chevrolet would do that. The other engine had main bearing clearances which I would consider too loose. On the "more than necessary" side of the tolerance but again not enough to cause a problem. The rod bearing clearance in both engines was very good as were all the other clearances.

I noticed GM continues to use "selective fit bearings." In case you're not familiar with this term I'll give an explanation. Selective fit bearing half shells come in increments of .0001" of a inch and you can tell when you have one by looking at the back of the bearing. For instance, it may have a number like .0003 or .0007 which shows how much that particular shell varies from the standard. Some years ago, when they first started this procedure, one of the engine building books talked about it and claimed that it was a way for them - on the assembly line - to correct for main saddle alignment discrepancies. Actually they are used to compensate for production variances in crankshaft journal diameters, not for saddle heights. There is no production inspection of saddle heights. I don't know if there is an inspection for saddle bore diameters. As with any mass production process things can change - drift. That is why you must have some kind of an inspection process. The General uses, as does everybody, a statistical process control (SPC) inspection. It is done "on line" and not every engine is inspected. They couldn't. Chuck says (and this information comes, again, from Chuck Maguire) there are three engine lines at the Flint plant. Each line assembles, starts, and balances around 1800 engines per day. That's just one type of engine. Five thousand a day and most of the assembly is still done by hand! But they don't build the same engine type continually. When it comes time to build the ZZ3, for instance, they shut down production - fill the bins with ZZ3 engine parts and build them for a few days and then won't build them again until they have depleted the warehouse. With those kinds of numbers they're not doing much measuring. Every so many hundred, or thousand, they will pull one and measure it. If you happen to get one after a machine adjustment, you're going to get a good engine. If they take a measurement and find that something has "drifted", depending on what it was, they may or may not pull the finished stock and fix them.

It's puzzling how there can be such a wide discrepancy in bearing clearances between two engines. Could this be the difference between assembly lines? We had to align hone the one with the tight clearance and change the bearings. By align honing with the crank and bearings "in hand" we can get the clearances right where we want them.

I remember the "old days" of the LS-6 and LS-7 big block crate engines - you had to take them apart and make sure there wasn't anything extra in them, or the corollary, make sure everything was in there that was supposed to be. That's just the way you had to deal with them. We saw one with rings missing on some of the pistons - the General is not exempt from employee problems. Now days ZZ3's are fired, with a propane hood, and run for a short time. At least these kinds of problems should be behind GM.

Engine number two also had a problem which would, sooner or later, have certainly caused a failure. When Chevrolet went to the new roller cam they also changed to a slotted rocker arm to eliminate the need for a pushrod guide plate. The rocker has a slot which keeps it centered on the valve tip, hence the need for the guide plate is eliminated. In fact, if you were to use the guide plate and the slotted rockers together, the pushrod would rub on the guideplate and eventually wear itself through. Well, this engine had both the guideplates and the slotted rockers. A bad situation and certainly a screw-up at the factory.

What are we to make of all this? I, for one, don't consider this to be a sad commentary on the quality of automotive engines. When you consider the amount produced per day you have to expect a few "bad apples" in the barrel. Be that as it may, in the aircraft situation you may not survive a bad apple. It seems I have cast production engines in a negative light. I'm not trying to generate hand-wringing about the deplorable state of assemble line quality, but if you plan on just plucking one from the box and installing it in the aircraft, perhaps a realignment of expectations is in order.

Engine Packages: We can offer many different engine displacements for both the small and big block Chevy and Ford engines. We can build small blocks up to 462 cu. in and big blocks up to 805 cu. in. There are significant torque increases with more displacement. However, when building long stroke engines one might make compromises in RPM, TBO or the perceived confidence level. We build approximately twenty Chevrolets to every Ford. Therefore we feel more comfortable with the Chev but the Ford isn't much different and there is no reason it should not perform as well.

The details of each engine combination is lengthy and there is no need to go into detail on them here. We can send a separate data packet on these if requested. These various engine combinations can be built with aluminum or cast iron blocks, wet or dry sumps, carbureted or fuel injected, and many combinations in between. In other words, we can build many different engine sizes and component combinations to cover everyone's requirements concerning cost and confidence level.

There will be a new Chevrolet aluminum small block - scheduled for release in June - that should become the ultimate small block if big cubes is what you want. It has a siamesed bore, raised cam tunnel with big block cam bearing sizes, 9.5" deck (.5" taller than stock) and can accommodate strokes to 4.25". 4.125 X 4.25 = 454 cubic inches. The computer model I ran, using the default airflow amount showed 614 lbs/ft of torque at 3758 RPM and 571 HP at 4960. Wow! Of course the real torque and horsepower numbers will vary depending on what cylinder head is used. For instance, using the CNC (computer numerical control) ported Corvette heads (same as the ZZ3) the program estimates 583 lbs/ft torque at 3530 RPM and 482 HP at 4660 RPM. Switching to the latest 18 degree CNC ported Chevy head raises the torque to 648 lbs/ft but it puts the peak at 4663 RPM. The horsepower climbs to 705 at 6155 RPM. That's serious power from a normally aspirated small block. Power also depends on how much airflow the camshaft allows the cylinder to access. We modeled these using a type 1 cam, which is a high-performance flat tappet and we help the program by using empirical airflow data. You can see that by juggling cylinder displacement and intake system airflow, torque and horsepower peaks can be put where you want them, but of course power will be affected as well.

A large displacement small block or big block aircraft engine should be built on a little different agenda than building a low RPM race engine. When you are using custom built components, you have some latitude in the design of the parts. No longer is it necessary for a major compromise between performance and reliability. You can focus totally on reliability. For instance, the connecting rods (Carrillo of course) can be built for a larger diameter wristpin and the beams can have a hole EDM'ed (electron discharge machine) through them for pin oiling - like we do for turbocharged engines. We would still use titanium valves, even though this is not a high RPM engine, simply because the titanium valve is stronger in a high heat environment than a stainless valve. Since they are also considerably lighter there is less stress on the whole valvetrain. The pistons can be made with a greater CD (compression distance - distance from the center of the pin to the piston deck) which will allow more strength in the dome and keep more heat out of the upper ring. The upper ring thickness can be increased to decrease piston temperature. Crankshaft main bearing diameter can be increased because bearing speed is lower. This increases journal overlap thereby increasing crankshaft stiffness. In turbocharged engines the block is modified to incorporate oil-jet cooling to the bottom of the pistons. We would also change to inconel exhaust valves which hold up better under the higher combustion/exhaust temperatures of boosted supercharged engines. Inconel valves are twice the price of titanium ones.

Accessories: Almost everyone we have talked to about kit aircraft has expressed a desire to buy everything from the firewall forward from as few sources as possible. This would certainly simplify things and minimize problems with parts not being compatible and worse yet - conflicting opinions as to what will work and what will not.

We are attempting to supply everything the owner needs except the gear-reduction and prop. We are going to test the feasibility of running the gear-reduction mounted on customer's engines on the dyno. This way we can put load on it, not to mention, being able to measure how much horsepower it uses (friction horsepower). Since we dyno test every engine we build (you can't get it any other way) this gives us the opportunity to test components on the customer's engine in the same manner that they will be used on the aircraft. This should go a long way in making sure everything works. There should be no surprises when the engine is fired up in the aircraft. It also makes us feel better developing a complete package. We don't have to worry that someone is going to hang something on the engine that may change its systems in a way that may not be predictable.

Exhaust System: We have built and tested, to date, two exhaust systems for the P-51 replica. Their purpose is to give the aircraft the original V-12 look. To do this they must exit the cowling at approximately valve cover level and be a little offset from the center (in the fore/aft direction) of the engine. We built a log style system similar to what FEW is using on the prototype. When George Bertwell was at FEW he took measurements and made drawings. We constructed the headers from his drawings.

Building these headers was not a lot of fun. The first two attempts were failures. One thing we learned is that they can't be built totally from stainless steel. We have built several sets of stainless steel headers in the past and haven’t had any problems, but, they were all individual port types. That is; none of the primary pipes were connected with a common header flange or to each other. Because of stainless steel's high thermal coefficient of linear expansion the P-51 headers warped badly even when bolted to a head and carefully TIG welded. The 2" stainless log also warped badly. Since the Corvette heads have a slightly different exhaust port centerline than other small-block heads we had to have the stainless header flanges CNCed by our machine nerds. Changing to mild steel fixed the warpage problem. When I switched to a mild steel one-piece header flange I machined them myself.

I built the first set with 1.5" outlet tubes (the six that you see) and the second set with 1.25" outlet tubes. I was told that the smaller tubes might look "more authentic" to an aircraft nerd and also that 1.25" tubes may make more power by a header nerd. That didn't make sense to me and if I had dynoed the 1.5" set before I had built the 1.25" set I might not have ever built the smaller set. But I did. And I'm glad I did.

Since we had last dynoed George's 400 we have learned a lot about exhaust systems as a result of development programs by race teams which rented dyno time from us. When we rent dyno time to race teams and such, it often happens that we learn right along with them. Teams that rent our facility also want us to act as advisors to the testing procedures and horsepower development. Since we have to be there, we are privy to the information they learn. It's nice to be paid while you are learning. These extensive exhaust system tests have yielded exciting insights. We now know, for example, how critical the exhaust collector is to the fuel curve of a carbureted engine, especially at low RPM.

When we put George's engine back on the dyno we re-baselined it with the same Corvette exhaust headers that were used in the original testing. The numbers were within 1% of where they had been. We had been pleased that the engine made the power it did with that exhaust system. Now when we put on our dyno headers we gained over twenty lbs/ft of torque. It was mostly the special collector design that was responsible for this gain.

When we tested the first P-51 log style with the 1.5" outlet we lost 25 lbs/ft of torque at the torque peak as compared to the Corvette headers. A 45 lb/ft difference from the dyno headers. Keep in mind that this is a 400 cubic inch engine and with a 350 there would probably be less loss. George was not concerned about the power loss because he was way over his power goal anyway. However, the bigger concern should be for the amount of heat this configuration will put into the engine compartment. Any tubular steel exhaust system will glow red hot even at two-thirds power output even with airflow around it. All race cars operate in this mode. Since this log is within the cowling there will be a lot of heat dumped into the engine compartment. I have pictures of these glowing on the dyno. If you're interested in seeing this let me know and I will send you some pictures.

In conclusion I would say that these log style headers with 1.5" outlets will not appreciably hurt power when used on a 400 cubic-inch or less engine. I think a better solution, one that will reduce the power loss and minimize the heat, would be to use a system that had individual tubes - one from each exhaust port - then add two dummies if you want to retain the original look. The bad news, since they are not tied together, is that you can only have the O2 sensor measuring from one cylinder. The best cylinder to monitor could be figured out on the dyno. These individual tubes could also be built from stainless which would eliminate the need for a coating process and they would last a long time.

Bertwell Engine Test: For some of you who are interested in what other kit builders are up to, we recently had George Bertwell's engine back on the dyno for further testing and development on the ignition, exhaust, oil and cooling systems. After these tests we dynoed it upside-down to test the negative G package (more on these tests next time). From the beginning we had a very low EGT on cylinder number one. After changing probes, injector nozzles and various other parts we did a leakdown test. When I first put pressurized air into the cylinder it had 95% leakage, all coming by the exhaust valve. While we stood there discussing what to do next the sound changed and suddenly the pressure came up and the gauge read 10% leakage - a normal number. We soon realized that the hydraulic lifter wasn't bleeding down properly - too low leakage. It was acting like a solid lifter. I took the lifter out (we were lucky to be able to do so without removing the intake) and took it apart. These things have very tight clearances so debris was the expected culprit. I could find nothing wrong with it nor could I see a piece of debris causing a blockage. I put it back together and when we restarted the same problem reappeared. Leakdown was high as before but eventually returned to normal. Why, pray tell, did it not behave this way before? This engine had a lot of dyno time on it. When we pulled out the old data, number one cylinder showed no sign of a problem. Why now? The lifter supplier says they will have none available for at least 8 weeks - knowing them that means 16 weeks.

This was not our first problem with hydraulic roller lifters or with flat tappet hydraulic lifters for that matter. Two years ago we had a customer's engine on and off the dyno for months while mapping E.F.I. and dealing with mechanical problems. During one of the "engine apart" stages it was noticed that the rollers were eating themselves through the lifter bodies. Long story short - wrong heat-treat on the bodies. The manufacturer (not Rochester Products) shipped thousands of these to their vendors and of course these people didn't want to acknowledge the problem until they had sold them all. I do not know what the moral of this little story is, but, it may be that the more moving parts the less reliable things become. It certainly tends to sour one's confidence in hydraulic lifters. We do know that we can't be shipping engines that may cause a valve to burn or cause a customer to become upset, just because of the touchy nature of these things. In one of my conversations with Chuck Maguire he shared some information that shed light on why we have never had a problem with any of the hydraulic lifters in the ZZ3s.

Rochester Products makes the lifters for General Motors. Every GM lifter goes through an inspection. One hundred percent of them. They check for bleed-down rate and they are sorted according to their bleed-down times. You will not get an engine in which some bleed down fast, others slow. They may be slow or fast but they will all be the same. The reason is low speed emissions, because bleed-down effects the overlap. At high speed bleed-down doesn't make any difference. There is a tolerance window, they must not be too high or too low. Chuck confided that in the past Cadillac took all the fast ones because they had idle problems and that is how they fixed it without having to change the cam. Right now Buick is using the fast ones and Chevrolet is using the slow ones.

Apparently you don't get this kind of inspection when you buy hydraulic roller lifters from the aftermarket companies. They just buy the lifters and attach their own latch bar mechanisms. They give the impression they manufacture them, but most of these aftermarket lifters are made by Sealed Power Corp.

The Rochester lifters are not available for use except on new GM engines. The only practical solution, at this time, would be to use solid lifters instead of the hydraulics. Hydraulics, in contrast to solid lifters, are perceived to be quiet and require no periodic adjustments. Certainly noise is not going to be a issue when you're already sitting right behind an unmuffled engine. The frequent adjustment problem can be addressed by using shaft mounted rockers. See my paper titled GOOD RIDDANCE.

A major concern with flat tappet followers is the break-in period. Since the lifter/lobe interface is the highest loaded point in the engine and is only splash lubricated it is very susceptible to failure during the lifter/lobe getting acquainted period. If a strict courtship ritual is not adhered to during this critical period the relationship can fail with disastrous results. If the cam lobes and lifter faces are machined properly, the cam has been parko/lubrided correctly, and proper break-in procedures are followed the odds of failure are minimal. This is another place where the dyno is nice. Even if there is a failure, we should know it before we were very far into the dyno program. **The dyno is the ultimate quality control machine.** With roller lifters there are no break-in concerns and solid rollers are very trouble-free. An advantage, besides less moving parts, that the flat tappet enjoys over the roller is that it can accelerate the valve faster. Low RPM applications are best for high acceleration profiles. With an engine that operates at lower RPM we recommend a flat tappet because it can deliver more power (if this inherent characteristic is exploited) than its roller counterpart.

Re-drive Comments: We are not in a position to endorse any one reduction unit over another. As the engine builder however, we recommend components that help make our job easier. First of all, it would be nice if normal engine rotation is maintained. We have built reverse rotation engines and they require no special technology. If you're using the ZZ3 you will have to get another cam and distributor gear. No biggie, I guess. The wrist-pin offset will now be reversed to the minor thrust side. Still, no problem. I use to build my race engines that way and you won't be able to hear the piston slap over the exhaust noise. There are minor changes required to the crankshaft oiling and oil pump. Bigger problems are encountered in the cooling system. Reverse rotation means we cannot use a water pump with a directional impeller. Hence, water flow will suffer.

A more practical problem is with our dyno. It has a directional impeller in the absorber and can only handle a limited amount of torque in the "reverse" direction. We dynoed reverse rotation engines on our old dyno but so far we haven't had one on our new dyno. We have handled over 1200 lb/ft torque in normal rotation. You would think it would at least absorb 400 lb/ft in the reverse direction. SuperFlow (the manufacturer of our dyno) was not willing to give us an answer.

With a water pump, oil pump and alternator already driven from the front of the engine it would be a real hassle to also mount an oil pump for the constant speed prop. Some re-drives have provisions for mounting a pump to do this. We like this idea. An idea we don't like is sharing engine oil with the oil for the reduction gear. It seems akin to sharing your tooth brush. We don't know how much debris one of these things will generate. We do have filters of course, but it's nice to know which device is generating the debris.

The chain drive system is probably a fine choice but there's just something about that many moving parts (each link) and the old saying that "the chain is only as strong as its weakest link."

We also think a belt drive would be a good choice for all of the reasons mentioned in GOOD RIDDANCE. But, as I understand it, there is no provisions for supplying oil to a constant speed prop.

There has been a recent failure of a gear-reduction unit because of a notch being placed in a shaft to facilitate machining. We have seen, from our own experiences, when there is a component failure we learn and the wisdom gained usually results in a "fix" that makes the component superior to what was originally intended.

Firewall: We have built a dummy firewall to mount in front of the engine while it is on the engine stand or dyno. This firewall will contain the same components as the FEW P-51 aircraft. This allows us to determine correct hose lengths, and test the engine with as many of the parts it will actually use.

Conclusion: Since I've probably overstayed (or overstated) my welcome I will conclude by saying that this market is new to us. Today, after nearly three decades of engine building, the experimental aircraft engine market has come to us as a refreshing change. This marriage seems natural. The significance of our experience is clear when the product is tested on the dynamometer. We are constantly testing new parts and combinations for big and small block Chevrolets, not only for people who rent dyno time from us but on our five test engines as well.

Dependability transcends performance, this has always been the basic axiom with aircraft engines. We like to build engines that provide both, but we understand that not everyone wants, needs, or can afford the ultimate engine. So, to keep costs in line with the typical aircraft builders budget, we must do a reality check on the overkill of some components. The easiest way to keep costs down is to keep the horsepower down. If 340 horsepower and 380 lb/ft torque is adequate for your needs, our base engine will suffice; if your confidence level doesn't exceed the realities of production parts.

Engine building is not arcane or black magic. It isn't particle physics - almost anyone can do it. But what anyone can't do is assimilate experience without having lived it. We feel that some folks take an overly simplistic view of the engine building process. They can stray from their domain of experience, maybe not in assembly ability, but in the selection of parts for quality and compatibility. In the engine building business it is easy to be deceived by appearances. The selection of the correct components is vital for successful results. We have spent half a lifetime separating the wheat from the chafe, not only with components, but techniques and theories as well. This has been expensive but it is the only way it can be done in this profession. That's because most manufacturers, naturally, try to make their product out to be better than it is. To modify a Mark Twain'ism, "the difference between the right part and the almost right part is the difference between lightning and the lightning bug." As any engine builder knows, several variables are at work in the build-up of an engine. It is like making a cake from scratch - lots of ingredients to pick from, weigh out, mix together, and bake properly. When the baker is inattentive or uses poor quality ingredients, no one will want the cake. In our cake, however, a mistake could have more serious consequences.

Certainly, one advantage of S.E.D. is that we have a lot of experience with V8 race engine development and evolution for cars and boats, both sprint and endurance. This dovetails nicely with performance aircraft engines. Since building engines is our profession, we live in this industry every day and have our fingers on the pulse of the industry. Over the years we have acquired a broad base of knowledge resources. These range from people deep within the car companies, to manufacturers, suppliers and other engine builders.

There are less expensive ways to build an engine for this application, however we won't compromise ourselves or our reputation. We feel our reputation will not be damaged if we stick to our convictions regarding conscientious engine building.

We started out to write a simple newsletter but, as usual, got carried away. We will send this to everyone on the FEW customer list. If you would like to receive the 21 previous papers and Newsletters that we have written about engine building and testing let us know by calling or faxing us a note. We now have a fax-modem in our computer and try to have it on from 8 am till 11 PM seven days a week. Computer components are a lot like engines components, they don't always work like they're supposed to. So if it doesn't go through the first time don't give up. Our fax number is 503-626-7003. Our old fax number is still available - 503-641-7266.

Pat Usher
Sunset Engine Development

P.S. A quote from Herschel Smith's book AIRCRAFT PISTON ENGINES.

"The old idea of getting an engine from a low-mileage wreck and putting it directly into a nice little plane is largely out of the window unless you fly out of a low-traffic airport in flat country. A proper conversion costs money."