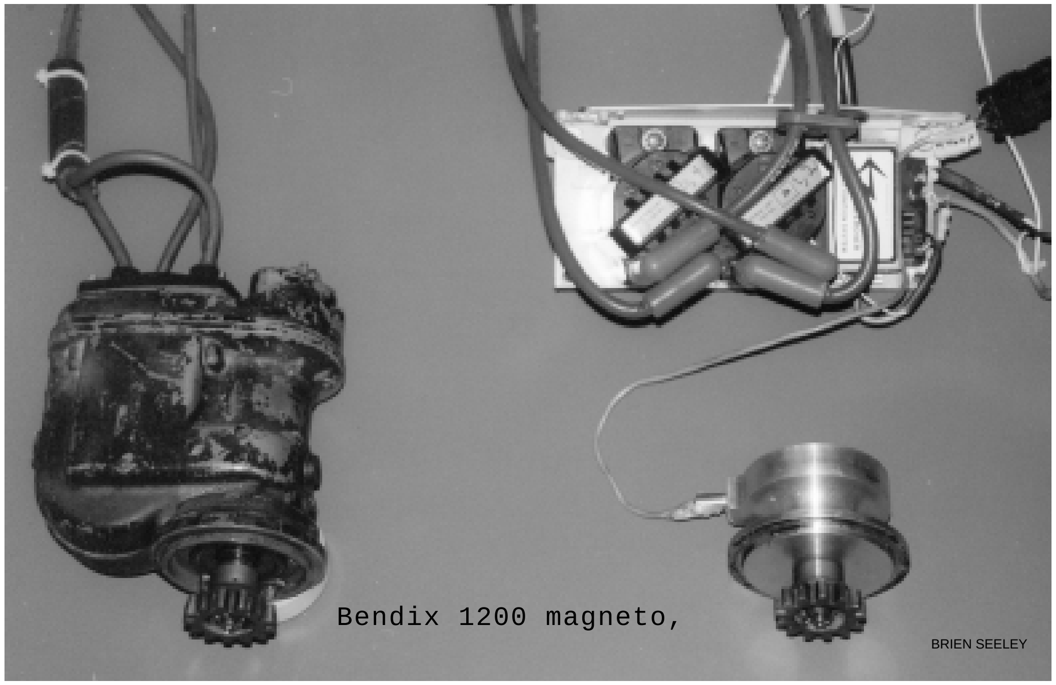
AIRCRAFT RESEARCH REPORT

Ignition Dynamics I

BY BRIEN SEELEY AND THE CAFE BOARD


Bendix 1200 magneto,

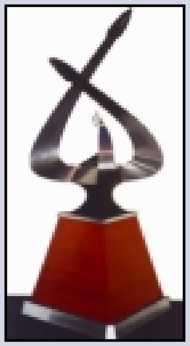
BRIEN SEELEY

This is the first of three CAFE Foundation research reports on aircraft ignition systems. Part I discusses basic operational and design considerations while Part II presents comparative flight test results. Part III will present the results of ignition system bench testing. A more comprehensive version of each report will be available at www.cafefoundation.org

BACKGROUND

The CAFE 400 flight efficiency races of the 1980's encouraged innovations that would improve the performance of light aircraft while reducing their fuel consumption. One such innovation was the use of electronically advanced ignition timing when operating with reduced manifold pressure at very lean mixture settings. Some of the aircraft that won the CAFE 400 races employed this technique to significantly improve their MPG score.

In the last 10 years, high energy electronic ignition systems for reciprocating aircraft engines, particularly in experimental aircraft, have been developed into off-the shelf, bolt-on products. Although their popularity is increasing, wider use of electronic ignition systems in aircraft has been limited by concerns regarding battery dependency, reliability and the safety of using ignition timing advanced beyond that specified on certificated engines. Claims of up to 20% greater fuel economy and up to 7% increase in horsepower have been made for these systems.[2,3] The CAFE Foundation performed extensive flight performance testing of electronic ignition systems during 2001. To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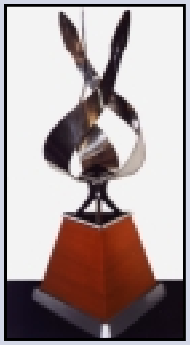

properly evaluate the test results, a review of basic spark ignition engine operation is helpful.

MAGNETOS

In conventional aircraft magnetos, a high voltage arc crosses the spark plug electrode gap at the desired ignition timing point, typically at 25° before the piston reaches top dead center (25° BTDC). For the sake of simplicity and to avoid detonation, the 25° BTDC timing is held constant at all power settings and RPM's.

The peak voltage demanded from a magneto by a properly gapped aircraft spark plug seldom exceeds about 12,000 volts. The spark voltage and duration depend upon several factors as shown in the table below.[4]

An increase in:	Makes voltage	Makes duration
Plug electrode gap	increase	decrease
Altitude, non-turbo	decrease	increase
Mixture richness	increase	decrease
Water vapor	increase	decrease
Compression ratio	increase	decrease
Air temperature	decrease	increase
Gap airflow	increase	decrease

Because the spark plug electrode gap is a main determinant of the voltage required to ‘fire’ the spark plug, magnetos typically use smaller gaps (~0.018") than high energy ignition systems (~0.030"-0.040"). If the spark plug gap is set too wide, the higher voltage discharge that this demands from the magneto's coil may ultimately cause the coil to short internally, overheat and fail. Gaps that are too small, although they increase spark duration, are subject to fouling and consequent misfiring. It is therefore very important to set the proper electrode gap when servicing aircraft spark plugs.

Use of larger magneto coils with higher voltage capability is limited by the tendency for stray arcing to occur within the magneto’s distributor, especially at high altitude where it takes less voltage to initiate such a stray arc. The Bendix 1200 magneto, shown in the first photo, was introduced circa 1965 as a modern “high altitude” magneto. It uses an extra large high voltage coil and has exceptionally wide separation of its distributor electrodes to prevent stray arcing. Its coil is capable of generating as much as 30,000 volts.[5]

In the quest for better fuel economy, automotive engineers have developed distributorless ignition systems that allow the use of even higher energy sparks without unwanted arcing. High energy sparks are better able to ignite very lean mixtures.

COMBUSTION DYNAMICS

Ideally, the rise and fall of cylinder pressure is timed by the ignition event so that as much of the pressure as possible is used for the mechanical work of pushing the piston. The ignition timing that accomplishes this is called "maximum brake torque" (MBT) timing. MBT timing must also account for the piston’s ever-changing mechanical leverage on the crankshaft during the expansion stroke. For a given engine at a given power setting, MBT timing causes the peak cylinder pressure to occur slightly after top dead center, often in the range of 11°-16° ATDC. Igniting the mixture too early or too late causes a reduction in power. Likewise, if the mixture burns too slowly, burns incompletely or extinguishes prematurely, power loss will occur. Deviations from MBT timing of +/- 3° BTDC produce only 1-2% reduction in torque, so that cycle to cycle timing accuracy of 1° should generally be adequate to sustain near optimum torque.[6] See Figure 1.

The details of the propagation of the flame front created at the spark plug exert an important influence on fuel economy and power. The speed and direction of the flame front's dispersion are mainly influenced by gas flow (swirl and turbulence), fuel/air mass ratio, and the homogeneity, atomization and exhaust gas dilution of the mixture. Ideally, the fuel mixture burns smoothly and completely at the proper rate and does not explode or detonate.

FUEL MIXTURE

Most reciprocating aircraft engines are equipped with a mixture control to allow adjustment of the leanness or richness of the inducted fuel to air mass ratio (or weight ratio). The exhaust gas temperature, speed of combustion, ideal ignition timing and engine power all vary with changes in this ratio. When flying at altitudes above about 5000 feet, appropriately leaning the mixture improves power, economy and engine vibration.

Gasoline powered engines typically operate with fuel/air mass ratios that vary from a lean value of about 0.056 to a rich value of about 0.083. For

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IMPORTANT NOTICE

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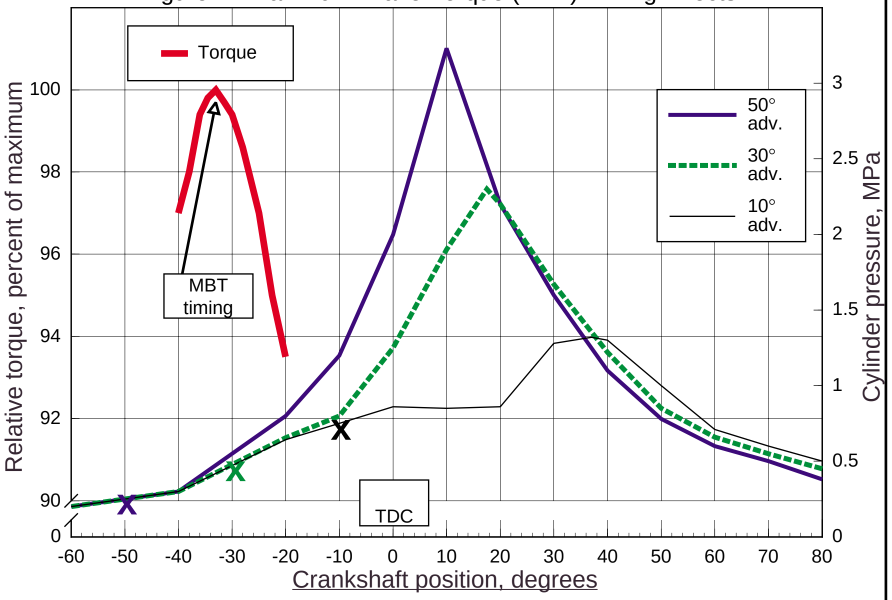
Figure 1. Maximum Brake Torque (MBT) Timing Effects



Spark advance effects on cylinder pressure and torque. "**X**" signifies ignition point.

takeoff at full power near sea level, fuel/air ratios are often enriched to as high as 0.11 so that excess fuel can serve as a coolant and help prevent detonation.

Depending on the fuel's chemical composition, a fuel/air ratio of about 0.065 to 0.067, produces a "stoichiometric mixture", meaning that it has the chemically correct proportions of fuel and oxygen. A stoichiometric mixture will burn completely, oxidizing all of the fuel molecules with little or no residual oxygen. It produces the highest or "peak" exhaust gas temperature (EGT) for a given manifold pressure and RPM and requires the least amount of ignition energy to ignite. Fuel mixtures that are leaner or richer than stoichiometric will produce cooler EGT values.

Flame speed varies dramatically with the fuel/air mixture. As the mixture is leaned from the stoichiometric ratio, it burns progressively more slowly. As the mixture is made richer than stoichiometric, flame speed progressively increases, up to a fuel/air ratio of about 0.080, which is the fastest burning mixture possible. As the mixture is enriched beyond the 0.080 ratio, it will burn progressively more slowly.[7]

Maximum horsepower,, and thus maximum true airspeed, is produced by mixtures that are about 100° F below peak EGT on the fuel-rich side of stoichiometric.[8] Such mixtures are called "100° F. rich of peak" (ROP). As the mixture is leaned from this "best power mixture" point, power and airspeed steadily diminish, while CHT rises slightly to peak at around 50° ROP. The flight data in Figure 2 illustrate these phenomena.

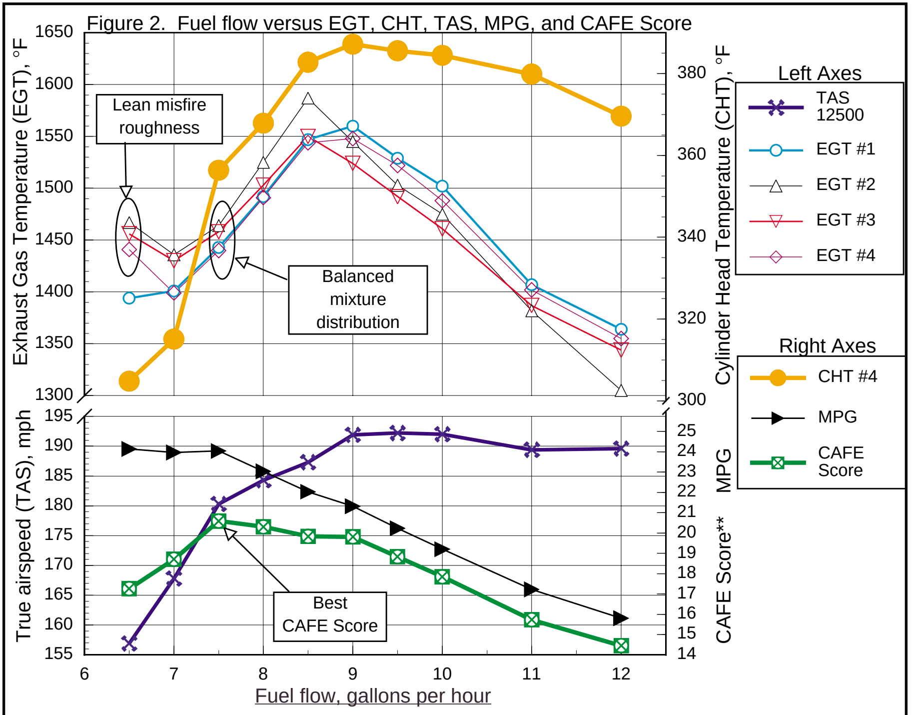
A fuel/air ratio of about 0.059 gives an EGT about 50° "lean of peak" (LOP) and this has popularly been considered the mixture for best economy or best miles per gallon.[9] Actually, the best economy mixture is that which delivers the lowest value in pounds of fuel per horsepower per hour for the engine as a whole, a term defined as the engine's brake specific fuel consumption, or b.s.f.c. Piston engine b.s.f.c. values can range from about 0.38 to 0.60 lb./hp/hr. and vary with mixture, manifold pressure, RPM and ignition timing. The b.s.f.c. serves as a yardstick for the fuel efficiency of different engines and power settings and is an important determinant of range, payload and cost of operation.

An engine’s best (i.e., lowest) b.s.f.c. occurs at a particular MBT ignition timing that will vary depending upon the engine’s power setting. The more the mixture is leaned from stoichiometric, the more advanced will be its MBT ignition timing, because the leaner the mixture, the more slowly it burns.

Figure 2 indicates that, for the CAFE testbed aircraft, best MPG and maximum relative CAFE score occur at an EGT that is over 100° LOP, where the peak CHT has fallen by about 50° F. This unusually lean mixture operation is made possible by some modifications made to the test engine’s induction and exhaust systems.

From Figure 2, the average peak

Figure 2. Fuel flow versus EGT, CHT, TAS, MPG, and CAFE Score



Mooney N6057Q: Lycoming IO-360A1B6X engine, dual Bendix 1200 magnetos @ 25° BTDC timing. 12,500' density altitude, wide open throttle, 2550 RPM, hottest cylinder #4, 2455 lb flying weight, wing Barograph #3. **Relative CAFE Score = $TAS^{1.3}$ x MPG

EGT occurs at about 8.7 gph at 2550 RPM and wide open throttle at 12,500' altitude. Assuming that represents a stoichiometric fuel/air ratio of 0.066, and noting that the leanest fuel flow for smooth operation is 7.0 gph, the test engine's lean operational limit with dual magnetos can be calculated to be a fuel/air weight ratio of:

(7.0/8.7) x 0.066 = 0.053 fuel to air

DUAL IGNITION OPERATION

Aircraft engines must time their ignition so that the resulting flame front smoothly propagates across their large diameter combustion chambers within a short time period. Initiating flame fronts of finite speed from two separate spark plugs helps assure that all of the fuel mixture will be consumed before the exhaust valve opens. Aircraft engines typically have uneven mixture composition with significant combustion chamber turbulence and swirl. Two spark plugs are better than one for igniting mixtures of variable compositions and flow velocities. In addition, dual spark plugs provide redundancy and reduce the tendency for knock. For these reasons, aircraft engines typically use two separate spark plugs.[10]

Lycoming states that a conventional aircraft engine loses about 3% of its power when one of its two magnetos is turned off.[11] EGT rises during single magneto operation. These effects are due to fuel burning *after* it leaves the cylinder. This late burning can be explained as follows:

During single magneto operation, only one of the two spark plugs per cylinder is firing and its flame front must therefore travel farther and thereby take longer to fully consume the inducted mixture. Standard dual magneto ignition timing is predicated on having both spark plugs initiate combustion, with each of their flame fronts having a shorter distance to travel. When only one plug fires, standard timing is too late, causing the mixture to continue burning after the exhaust valve opens. Optimally advancing the ignition timing can provide more 'burn time', so that the flame front from a single spark plug *can* more fully consume the mixture before the exhaust valve opens, and thus reduce EGT and produce more power. Likewise, if, during *dual* magneto operation, the ignition of a super lean mixture succeeds at only one of the cylinder's two spark plugs, slightly advancing the ignition timing improves power.

KNOCK

If the ignition timing is too advanced, the ignition pressure wave crossing the combustion chamber can induce the mixture at various other points in the chamber to spontaneously ignite. This produces undesirable irregular burning with intense pressure fluctuations, very high combustion pressure peaks and loss of power. The hammering or pinging sound that results is called 'knock' or 'detonation'. At high engine speeds, knock may not be audible. It can begin insidiously and progress as a vicious cycle of increasing temperature and knock intensity.

The sharp peaks in pressure and consequent high temperatures of knocking can quickly produce structural engine damage and engine failure. A typical result of light knock is an erosion of the piston crown that looks as if it had been heavily sandblasted. A borescope examination can sometimes detect such knock damage. Knock is the foremost reason to avoid excessively advanced ignition timing.

Susceptibility to knock is highest at mixtures that are stoichiometric or slightly richer than stoichiometric, precisely where many pilots have been taught to set the fuel mixture. Here, if one spark plug is fouled or misfiring, knock becomes even more likely. Knock tendency is much reduced at very lean, slow-burning mixture settings. High compression ratios and high inlet air temperatures increase knock tendency.

Ideally, ignition timing advance should be controlled by knock sensor in a closed control loop to continually operate just below the knock limit where MBT timing and, thus, best power are usually to be found. Unfortunately, knock sensing transducers work poorly in aircraft engines because of the high noise and vibration levels that exist.

LEAN MISFIRE

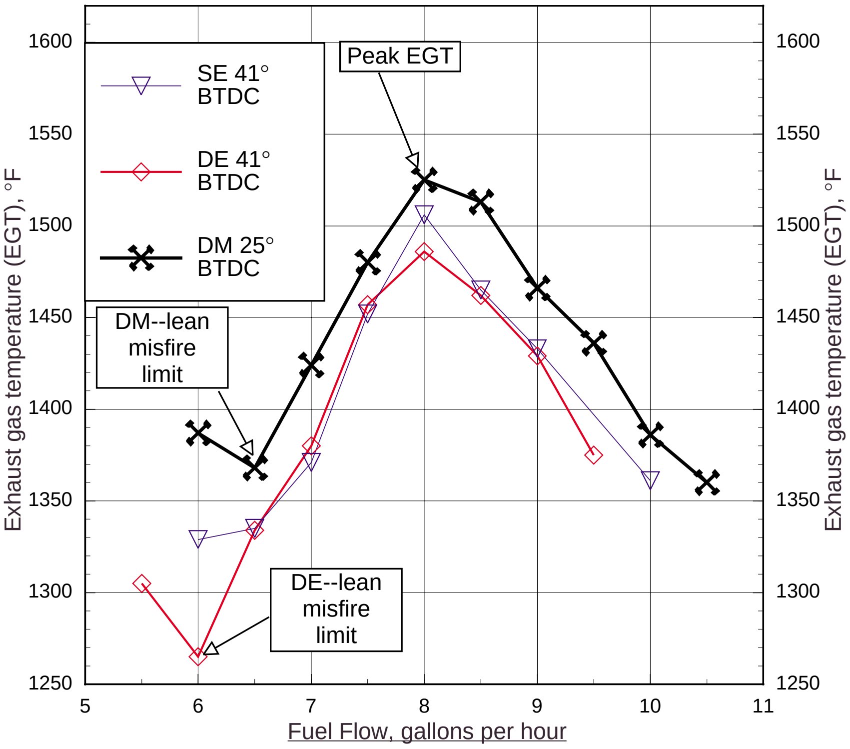
Flame speeds of 75 cm/s at stoichiometric mixtures slow by nearly one third to only 52 cm/s at the lean fuel/air ratio of 0.052. Diluting a stoichiometric mixture by just 20% with recirculated exhaust gas reduces the flame speed to only 23 cm/s.[12]

With very lean mixtures, some combustion cycles may burn so slowly that flame propagation is completed just prior to exhaust valve opening, i.e. too late in the cycle to do much work. In such a case, a large fraction of the energy release occurs late in the combustion cycle when changes in cylinder volume are more rapid, causing greater variations in cycle to cycle pressure and end gas residuals. With even further leaning, there is further power loss as some cycles occur in which the flame continues its slow burn *after* the exhaust valve opens, wasting energy and increasing EGT. This slight rise in EGT is a sign of lean misfire and may indicate that only one of the two spark plugs has succeeded in igniting the charge.

With further leaning, cycle to cycle fluctuation in peak cylinder pressure becomes increasingly erratic. At some point, this produces cycles in which the flame extinguishes prior to exhaust valve opening or fails to ignite at all, causing EGT to plummet. At this extreme degree of misfiring, engine roughness and vibration are unacceptable for continuous operation. Advancing the ignition timing at this point can sometimes restore smooth operation, extending the lean misfire limit and increasing power. See Figure 3, which shows the reduction in EGT from advanced ignition timing and the rise in EGT at the lean limit for different ignition systems.

As the mixture is leaned, uneven mixture distribution usually causes some cylinders to reach their misfire limit before others. The ability of the leanest cylinder to operate smoothly and without misfire sets the *practical* limit on the leanness of the overall fuel/air mixture that the engine can use.[13] The lean misfire limit is extended in engines with evenly balanced mixture distribution among all cylinders and such engines can therefore achieve lower b.s.f.c's. See Figure 2 showing the variations in individual cylinder EGTs at lean

Figure 3. EGT#4. Lean misfire limits of dual Bendix 1200 magnetos at 25° BTDC versus EIS-1 electronic ignition at 41° BTDC.

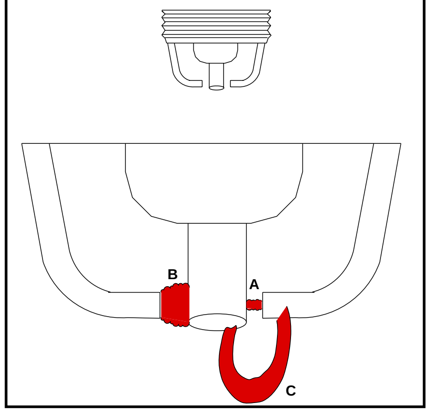


Mooney N6057Q in level flight at 15K density altlitude. Wide open throttle, 2550 RPM, stable TAS, digital acquisition device recordings. Cowl flaps fully opened. DM = dual magnetos. DE = dual electronic ignition. SE = single electronic ignition with one magneto.

mixtures (the “EGT spread”).

Max Conrad developed a simple method for finding an engine’s practical lean misfire limit. On his famous long distance flights in his Piper Comanche, his technique was to lean the mixture until the engine ran roughly and then enrich it just to the point where it would run smoothly on both magnetos but show slight roughness when operated on one magneto. Such roughness likely meant that the misfiring of one of the two spark plugs in the leanest cylinder was kept hidden by the successful firing of the fellow spark plug in that cylinder as long as both magnetos were operating. Although it delivered a maximum in miles per gallon for his record flights, this technique is not recommended by aircraft engine manufacturers.

Figure 5. Relative spark kernel surface area for magneto (A), high energy ignition (B) and high energy with gap airflow (C).



SPARK PLUGS

To assure that a self-sustaining inflammation process disperses rapidly away from the spark plug requires increasing amounts of ignition energy as the mixture is leaned beyond peak EGT.

Distributorless electronic ignition systems using large inductive coils can deliver higher spark energy and spark duration than those of a magneto system. This can be helpful in igniting very lean mixtures.

Most capacitive-discharge ignition (CDI) systems deliver a strong but short duration spark lasting about 100 to 300 microseconds. Some multiple-spark-discharge (MSD) ignition systems use a sequence of several brief CDI sparks in rapid succession to extend their effective spark duration. If these multiple sparks are delivered from separate, alternately firing ignition sources, the 'dead' interval between them can be diminished so as to approximate a continuous long duration spark of high energy.

The diameter of the spark can be thought of much the same as we observe that a lightning bolt can be either skinny or fat. The spark diameter depends upon its amperage. The length of the arc is ordinarily set by the spark plug gap, although mixture airflow can stretch a spark into a curved loop of much greater length. See Figure 5, “C”. Larger gaps require higher ignition voltage to successfully ionize the molecules between the electrodes. Sparks that are stretched by airflow into loop shapes require substantially higher energy to avoid being ‘snuffed out’. Because some degree of airflow, squish or mixture swirl is nearly always present, many engine designers shelter the spark plug electrodes in a somewhat recessed location in the combustion chamber to prevent such ‘snuffing’. Recent work suggests that a high energy, stretched loop spark can succeed in igniting super lean mixtures.[14]

The instantaneous power of the spark can vary dramatically. The finite packet of energy stored in an ignition coil can be delivered as a high power but very brief spark or, alternatively, as a lower power longer duration spark. A reduction in spark power in order to provide longer spark duration can be achieved by reducing the gap between the electrodes. Higher energy ignition systems afford enough energy to sustain good spark duration even when using plug gaps that are twice that of a magneto system.

A fatter spark across a larger gap creates an initial inflammation zone of much greater surface area than a skinny spark in a short gap. See Figure 5, “A versus B”. The larger this surface, the more likely it will ignite a very lean mixture and the faster its initial burning rate will be.[15] Conceptually, a large surfaced initial spark kernel can better ‘reach out’ to ignite the scarce fuel molecules nearby and launch of the flame front.

A long spark duration has a greater effect than high current in extending

REM37-BY plug with long-reach electrodes.

the lean misfire limit.[16] The swirl, turbulence and mixing of lean fuel/air mixtures can cause some regions in the combustion chamber to contain mixtures too lean to ignite at a given instant. Thus, the bottom spark plug of the combustion chamber may succeed in igniting the mixture nearby while its fellow top spark plug's arc fails to do so. A longer duration spark may allow the top spark plug to succeed in igniting its local mixture a few hundred microseconds later when the swirl places a richer mixture near its electrodes. Longer reach spark plugs that place the electrodes deeper into the combustion chamber may also increase the success of the plug in igniting locally lean mixtures.

By accelerating the initial spread of combustion, a larger, high energy spark kernel can allow use of slightly less timing advance than that of a lower energy (magneto) spark.[17] With fast-burning rich mixtures, this advantage of higher spark energy has less noticeable effect because the flame is easy to ignite with even meager spark energy and ignition energy applied after inflammation has occurred has only a modest impact on flame propagation.

EXHAUST GAS TEMPERATURE (EGT)

Exhaust gas temperature (EGT) reflects the leanness or richness of the fuel mixture. EGT is also an important diagnostic parameter. It rises significantly during magneto failure or during misfiring due to a fouled spark plug or other cause and it falls during knock or detonation.

The EGT gauge measures the average gas temperature just outside a cylinder's exhaust port and this reflects the relative temperature of the gases that bathe the head of the exhaust valve when the valve is open. Continuous operation at peak EGT thus imposes the maximum heat burden on the exhaust valve.

A cylinder's EGT represents a moving average from many combustion cycles in that cylinder. Values typically range from 1300-1650°F for normally aspirated engines at cruise power. Mixtures that are “rich of peak” (i.e., ROP or richer than stoichiometric) produce cooler EGTs because unburned fuel acts as a coolant. Mixtures leaner than stoichiometric (LOP) produce cooler EGTs because there is less fuel to burn and the excess of air literally “puts the fire out”. See Figure 6.

The 'EGT spread' is the difference between the highest and lowest EGTs among all of an engine’s cylinders at a given mixture setting. See Figure 2. At a fixed RPM and M.P., the EGT spread observed across a range of lean mixture settings reflects the evenness of the mixture distribution among all cylinders and can be used as a guide to modify the induction system to improve that distribution. Such modifications should only use EGT data obtained at wide open throttle settings due to the highly variable induction flows at part throttle.

MIXTURE DISTRIBUTION

Regretably, uneven mixture distribution plagues most aircraft engines where many cylinders share a common intake manifold, and fuel is poorly atomized. Large fuel droplets may distribute erratically through the induction manifold due to inertia and collimated airflows. EGT spreads of about 100° F with fuel injection and over 200° F with carburetors are fairly typical in such engines, especially at part throttle.[18]

In the automotive industry, extensive research has been devoted to improving fuel atomization and vaporization by carburetor and induction tract modifications that use nozzles, heated manifolds, vibrating plates, exhaust gas recirculation or other methods. Results show that fully vaporized fuel may not ignite quite as readily as ideally atomized tiny fuel droplets. Droplets of less than 15 micron diameter have been found to best follow the bending airflow path of induction manifolds.[19] Research has shown that lean ignition is more sensitive to atomization quality than to ignition energy.[20]

The tiny emitter orifices of the Ellison Throttle Body deliver a finely atomized fuel fog to the induction system. This fog distributes more evenly and ignites more readily than larger fuel droplets. This helped make possible the very lean mixture operation of the test engine used for this report.

The presence of excess oxygen in lean mixtures promotes more complete combustion because more collisions occur between fuel and oxygen molecules. This means less wasted fuel and an overall reduction in exhaust emissions.

In normally aspirated engines that have a narrow EGT spread, operating at below 70% power with mixtures 150-200° F lean of peak EGT offers the following benefits:

1) much cooler exhaust valves.
2) reduced cooling drag.
3) reduced emissions.
4) less noise.
5) less coking of the chamber.
6) less oil contamination.
7) reduced spark plug fouling.
8) less risk of detonation.

The reduced power and airspeed of such operation are compensated by a valuable increase in the distance between fuel stops. See Figure 2.

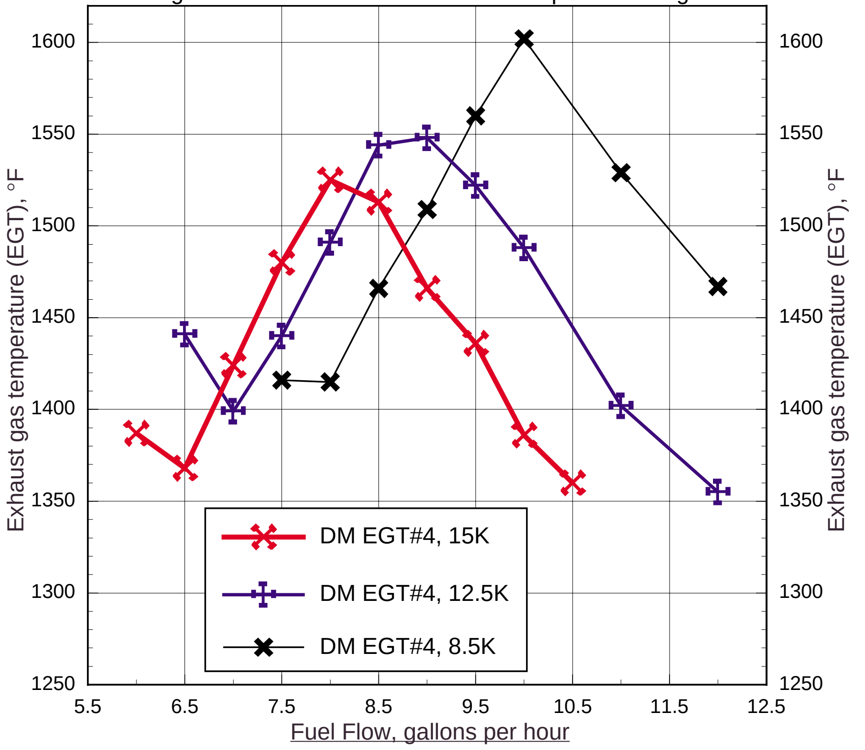
CONCLUSIONS

1. The ideal ignition timing (MBT timing) for a given engine varies with power setting, altitude and fuel mixture.

2. As the mixture is leaned beyond peak EGT (LOP), it burns progressively more slowly and therefore requires a progressively more advanced ignition point for maximum efficiency.

3. MPG and flight efficiency are maximized and cooling demand and emissions are minimized by operation at lean (LOP) fuel/air mixtures. Such operation is usually <u>not</u> possible (nor recommended by engine manufacturers) because of the un-

Figure 6. EGT varies with altitude and power setting.



Mooney N6057Q at 8.5K, 12.5K and 15K density altlitudes. wide open throttle, 2550 RPM, digital acquisition device recordings. Cowl flaps fully opened. Magnetos @ 25° BTDC. DM = dual magnetos.

even mixture distribution that exists in most conventional aircraft engines.

4. Magnetos require relatively small spark plug electrode gaps to avoid arcing in their coil and distributor. Although this limits their ignition power capability, magnetos generate more than adequate spark energy for the ignition demands normally encountered in conventional aircraft engines.

5. High energy electronic ignition systems with long spark duration and variable ignition timing can offer extended lean misfire limits and better fuel economy.

Ignition Dynamics II will present CAFE Foundation flight performance data comparing a standard magneto ignition to high energy electronic ignition that uses variable advanced ignition timing.

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