DETONATION

The difference between fast, even burning and explosion is up to the pilot

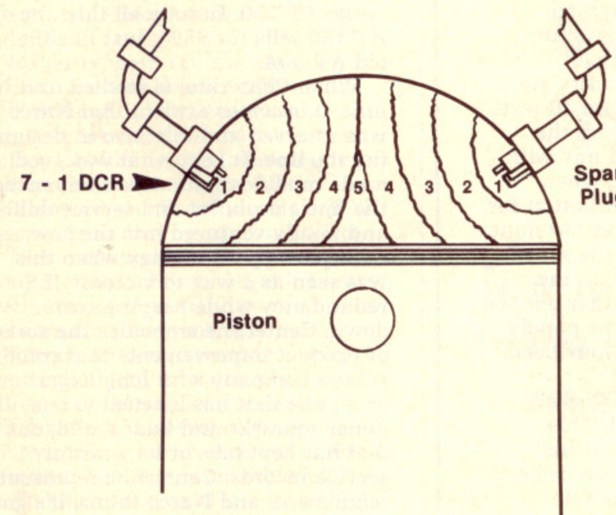

Figure 1

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■■ Some explanations on the reciprocating internal combustion engine state that ignition of the compressed fuel-air charge within the combustion chamber causes the mixture to explode, subsequently pushing the piston down within its cylinder. Under proper conditions that statement is not quite correct; however, if the mixture does explode it is more apt to push the cylinder head off its cylinder as well.

If the mixture doesn't explode, then what does happen? The fuel-air mixture in the piston engine burns at a controlled rate—very fast, but nevertheless controlled. Both processes are combustion, and the difference is simply rate, or speed, of combustion.

We could attempt to define an explosion as combustion of a violent behavior accompanied with extreme noise such as gunpowder. However even this isn't always true. For example, firing a gun would seem to fit the definition of violent combustion with extreme noise. While it may appear to be so, it really isn't.

In actual practice gunpowder does not explode when ignited within the breech of a gun; instead, it burns at a controlled rate. Indeed, if it did explode, the resulting pressures would burst the barrel before the projectile could accelerate the length of the gun barrel.

The gasoline that fuels the piston-type aircraft engine is capable of either controlled burning or exploding in the combustion chamber, and the deciding factor between the two isn't limited to fuel grade used. To understand explosive combustion one must first understand controlled or normal combustion.

Practically all reciprocating aircraft engines are of the four-stroke-cycle type meaning that four piston strokes are necessary to complete one cycle of events. During these four strokes (*intake, compression, power* and *exhaust*) a total of six events take place (*intake, compression, ignition, combustion, power* and *exhaust*). Ignition and combustion occur during the compression stroke or event. Now let's examine a normal or controlled combustion process.

During the intake event the cylinder is charged with a mixture of fuel and air. This inducted charge is then compressed prior to ignition. For ideal results the combustion process should be completed at or within a degree or two after the piston has completed its compression stroke. (At the top of its stroke, the piston is at top dead center, or TDC.)

Figure 1 illustrates a normal combustion process nearing completion. This process began with ignition from the dual spark plugs located at opposite ends of the combustion chamber. Once ignited, a flame front develops and rapidly advances across the top of the piston much in the manner of an advancing frontal passage in weather terminology. Ideally the two flame fronts will meet at the center of the combustion chamber a few degrees after top center, completing the combustion process.

The numbers in the illustration indicate the various stages of the advancing flame front. Number 1 is in the area of flame spread immediately after ignition. In Area 5 only a small portion of the original fuel-air charge remains to be consumed. If you were to measure the pressure and temperature in each of these numbered areas you would find that both are increasing to unbelievable proportions. At full power conditions the temperature in Area 1 might be around 450°F with an overall chamber pressure of perhaps 160 psi. Upon advancing through Area 5 you would see temperatures nearing 5,000°F or higher with pressures approximately 1,000 psi. Such high temperatures could easily melt any part in the engine if they were prolonged. However, the time of such exposure is quite brief. From ignition in Area 1 to completion of combustion in Area 5 is approximately 1/700th of a second. At that moment the piston descends rapidly in its cylinder and the expanding gases quickly convert this intense heat into work through a process defined as adiabatic lapse.

At takeoff rpm the entire four-stroke cycle is being repeated approximately 44 times per second, or one complete cycle occurs in 1/44th of a second. The entire power event occurs in less than 1/176th of a second at takeoff rpm. Even at these microsecond speeds combustion is still controlled and not explosive.

The smooth, even advance of the flame front in Figure 1 is termed flame propagation, or more often, just propagation. From the moment propagation begins, the temperature and pressure of the portion not yet burned is continuously elevated. All combustionable materials have a self-ignition temperature whereupon they will ignite of their own accord. This process is often referred to as spontaneous combustion. Its principle is utilized in the design of the Diesel or compression ignition engine.

The air temperature in the Diesel's combustion chamber near the end of the compression stroke will exceed considerably the ignition temperature of the fuel it burns. Thus when fuel is injected into this intensely heated air it will combust spontaneously. If the fuel was already in the Diesel's cylinder when compression began it would explode upon reaching its self-ignition temperature because all of the fuel would be elevated to ignition temperature simultaneously; consequently there would be no flame propagation. Instead, the entire fuel-air charge would combust at the same instant and that would be explosive combustion in the true sense of the word. This doesn't occur in the Diesel engine since the fuel is injected and combustion is controlled by rate of injection.

Spontaneous or explosive combustion can occur in the gasoline-fueled, reciprocating aircraft engine under a variety of conditions. Figure 2 illustrates explosive combustion occurring near the end of otherwise normal propagation. Here, propagation began in a normal fashion, but the rising temperature and pressure caused the remaining fuel-air portion near the end of propagation to reach its self-ignition point and subsequently explode. This type of explosive combustion is defined as detonation when it occurs in the reciprocating internal combustion engine.

Detonation produces a violent combustion chamber shock that acts upon the piston and related combustion chamber parts with sledgehammer force. It also releases heat energy with accompanying temperatures considerably beyond those of the normal propagation peak. In addition to the violent shock and excessive combustion temperatures, detonation also results in premature completion of the combustion process. That means a prolonged exposure to intense temperatures prior to adiabatic lapse relief during descent of the piston.

Perhaps this sounds trivial considering that the entire combustion process occupies only 1/700th of a second. Nevertheless it is critical. Even if the duration is prolonged by no more than 1/100th of a second it can elevate the residual operating temperatures of combustion chamber components. Such temperature elevations can quickly exceed the maximum for which the engine was designed and cause structural failure.

In the stock automobile, detonation can often be heard as a "pinging" sound from the engine upon full throttle application at low vehicle speeds. Usually it will cease when the throttle is reduced, but not necessarily. It could recur as incipient detonation at highway speeds and especially when towing a trailer. Then it may not be heard above road noise until it becomes a destructive reality. Certainly it is not likely to be heard above the takeoff noise in an aircraft. I have often been asked, "Couldn't you detect its presence with the cylinder head temperature gauge?" Perhaps so, but by that time the pieces have started coming out through the cowling. The most certain way to approach detonation is to know what causes it and then prevent it.

Probably the most certain cause of this destructive force

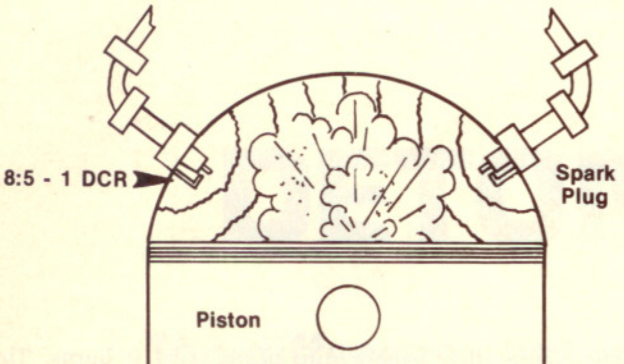

Figure 2

DETONATION continued

is operation with sub-standard fuel. Pure gasoline has a very low resistance to detonation and subsequently isn't satisfactory for use in engines above a design compression ratio (DCR) of 4 to 1. It's a known fact that more power and economy can be obtained from an engine simply by compressing the mixture more prior to combustion. Thus, the more you compress the mixture the more you get from the same amount of fuel. However, this approach is not without consequences, and there is a maximum limit as explained earlier with the Diesel engine.

Around 1928 the Ethyl Corp. invented a chemical called Tetra Ethyl Lead (TEL). This chemical, when added to gasoline in small quantities, effectively raises the fuel's resistance to detonation. Leaded fuels are given an octane number as a measure of their resistance to detonation. For example an 80 octane, or nowadays grade 80, fuel will satisfactorily perform in an engine with a DCR of 7 to 1 and not detonate under normal combustion and operating conditions.

Since the combustion temperatures and pressures rise rapidly with an increase in DCR more TEL must be added to fuels used in higher compression engines. Consequently, an engine having a DCR of 8.5 to 1 will require 100 octane fuel to operate at full power without danger of detonation. Now if that 8.5 to 1 engine were to be operated on 80 octane fuel, detonation would be certain at high cruise and at takeoff power settings. Destructive results can be expected.

Use of sub-standard fuel is perhaps the least-frequent cause of most detonation cases. Detonation can occur even when operating on the correct grade of fuel. Probably the most common cause is lean mixture operation at or above 75% power settings. Unless otherwise stated in your engine operator's manual, operation above 75% power should always be with a full rich mixture. The added fuel flow from a full rich mixture helps suppress detonation by performing a cooling function within the combustion chamber.

Still more lead could be added to the fuel to the point where this would not be necessary but then the lead fouling problems would be greater in the lower power ranges where pilots operate most of the time. The situation is not so critical that detonation is a certainty above 75% with anything but full rich, but then there also is no guarantee that it isn't. The added fuel flow is simply added protection against detonation and the conservation of fuel just isn't worth the risk of expensive damage to the engine.

Another cause of detonation is overboosting. This situation applies primarily to mechanical aspirated (MA), or supercharged, engines. There are many turbocharged engines powering general aviation airplanes these days, and they are highly susceptible to detonation when overboosted. The DCR on both supercharged and non-supercharged engines is fixed and cannot change. However, the MA engine has an aspirated compression ratio (ACR) as well. For example a 285-hp MA engine has a DCR of 7.5 to 1. Without its supercharger that is all it would ever subject the mixture to under full throttle, sea level conditions.

When supercharged to a limit of 34 inches manifold pressure the same engine at full throttle will compress the extra volume of fuel-air in its cylinders into the same 7.5 to 1 space. Only now there is more volume than before and the effect will be as if the engine had a DCR of 8.5 to 1. Thus we have mechanically aspirated the engine to an ACR of 8.5 to 1. As long as the limit of 34 inches manifold pressure is not exceeded the engine will not experience any greater combustion chamber pressures than it would with a DCR of 8.5 to 1 at 28.5 inches. Should you exceed 34 inches by any substantial amount even for just a few minutes you are asking for detonation.

Just six inches over the limit will result in substantially higher combustion chamber pressures. Higher pressures produce more heat and almost immediately the fuel's detonation resistance limits are exceeded. Now imagine the thermal runaway effects of a lean mixture to this overboost condition and you can have a real "wallet shrinker" on your hands.

Still another cause that can induce detonation is overheating. Attempting a takeoff with an engine that is at or quite near its redline temperatures leaves little if any margin of safety. Such a practice is an open invitation to detonation. Steep, low airspeed climbs, especially in hot weather, will usually result in near redline operating temperatures, another invitation to destructive detonation. If the mixture is leaned excessively under such conditions the situation is aggravated even further. Climbout mixture should be no leaner than necessary. Remember, the added fuel flow provides internal cooling and at a time when the engine needs it most.

Lean mixtures, especially at high power, can quickly summon detonation. Many a pilot has been led to believe that a lean mixture burns hotter than a rich mixture; therefore a leaner mixture will provide more power by virtue of more heat. Under normal combustion the highest temperatures are produced by a perfect, or stoichiometric, mixture. A perfect mixture contains the exact amounts of fuel and air whereby all are consumed with none of either left over. Neither lean nor rich produce as hot a combustion.

A rich mixture cools by virtue of heat absorption into the portion that did not burn for lack of sufficient oxygen. A lean mixture burns slower causing prolonged combustion duration and thereby elevating combustion chamber temperatures. It is this factor that causes the engine to operate at higher temperatures when operating lean. Earlier in this discussion numbers were provided with respect to the speed of flame propagation and the critical effect of slowing this process down by even 1/100th of a second. A lean mixture can do just that.

At 75% power and up such minute extensions of the combustion process can bring on detonation. Any reduction in propagation speed will result in longer exposure of the unburned portion to the intense heat of combustion. Even a combustion temperature as low as 1,000° F is still well above the self-ignition detonating temperature of the remaining unburned portion. Combustion temperatures at 75% power are considerably above 1,000° F.

No explanation of detonation would be complete without mentioning its nasty cousin preignition, sometimes called autoignition. Preignition is simply premature ignition of the fuel-air charge in advance of the regular ignition system. Perhaps the most common source of this phenomenon is hot spots caused by excessive carbon deposits in the combustion chamber. Sharp edges carelessly left in the combustion chamber during internal cylinder rework is another offender.

Spark plugs are often blamed for preignition, however I know of only two possible situations where this could be so. A spark plug that is loose and therefore unable to conduct away its heat from combustion to the cylinder head will overheat and act like a glow plug. A broken nose insulator with a fairly large piece missing will also overheat to the point of continual incandescence. I have never known a properly torqued spark plug to work loose or a nose insulator to break of its own accord. This usually happens when the spark plug is dropped on the floor.

Advanced detonation will soon cause preignition and vice versa. You can count on that. Preignition by itself causes rapid overheating and rough operation. A most common manifestation is the rough, jerky, but continued effort of the engine to run on after shutdown. This situation is often described as "dieseling" (the engine is behaving as a Diesel since both fuel and regular ignition are off). Supposedly the engine is "sucking" oil from the crankcase past the piston rings as a source of fuel for its continued operation.

The real culprit is preignition abetted by a leaky mixture control. The correct description for this condition is "abnormal engine run-on after normal shut down." Should this situation ever occur, do not allow it to continue until eventual stoppage. Immediately open the mixture control to full rich, turn the magnetos on if already off and run the engine up to approximately 1,000 rpm for a minute or so, followed by at least one minute at regular idle speed before shutting down. Run-on is usually prevalent in engines frequently operated or frequently operated at low power conditions for periods of short duration.

Detonation and preignition are in nearly every case the result of improper and/or abusive operation. Both are highly destructive and usually quite expensive. It is not unusual to see the entire top of the cylinder head blown out by advanced detonation.

The best remedial action if either detonation or preignition is suspected will be the reverse of what caused it. Reduce power, enrich mixture, open any and all cooling devices. Maintain your efforts until you are reasonably assured of its absence. Have your engine examined by an experienced A & P mechanic as soon as possible since you could already have internal damage. Prevention is still the best cure for these two "bad guys" and it's easier on the nerves as well. □