favorite ploy of "milling the head" has fallen into disrepute. But it also is possible to encounter trouble without recognizing it: There is a delicate balance between gains from increased compression ratios and losses due to increased temperatures—which appear not only at the piston's interior, but also throughout the crankcase, crankshaft, rod and all the rest of the engine's interior contacted by the air/fuel mixture. When these parts are hotter, the mixture's temperature is also raised, along with its free volume. Thus, the mixture's temperature-induced efforts to expand inevitably force part of it out the exhaust port, and as power is related very closely to the weight of the charge captured in the cylinder, this heating shows up as a power loss. The trick is to balance crankcase heating and compression ratio. There is an optimum combination for every set of conditions, but finding that optimum without heat-sensing equipment and a dynamometer is exceedingly difficult.

THE COMBUSTION PROCESS

Not too surprisingly, the equilibrium described is influenced by combusion chamber design—as is the point at which smooth burning gives way to the outright explosions we call detonation. This aspect, too, is widely appreciated, but not widely understood. In truth, most people have very little understanding of the events that follow ignition; events that are highly complex if studied with regard to their chemistry but really quite straightforward taken in less narrow terms. Much of the misunderstanding that exists has been created by the popular press, which insists upon saying that a piston is driven downward on its power stroke by a burning mixture. In reality, the burning of fuel in the cylinder is simply a means of raising the temperature of the working gas (air; actually a mixture of gases) and thereby raising its pressure. This relationship was formulated long ago by Boyle as

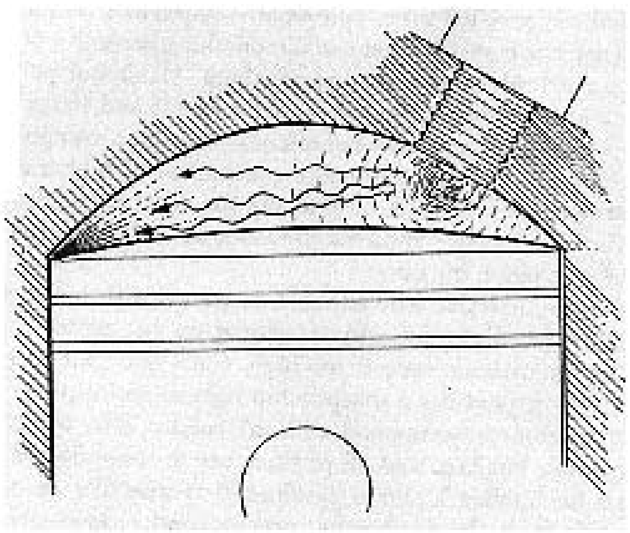
$$\frac{P_2}{P_1} = \frac{T_2}{T_1}$$

where, of course, P is pressure and T is temperature. The whole business gets complicated in the internal combustion engine by the changes in the cylinder's contents due to the combination of elements in the working gas with fuel, but it still basically is a case of raising the working gases' temperature and thus raising their pressure, and it is *that* which pushes the piston down and makes the horsepower. In fact, burning will have been all but completed by the time the piston starts downward on its power stroke.

Here, for anyone who cares, is what happens from the moment of ignition: Several thousandths of an inch of travel before the piston reaches the top of its compression stroke, representing somewhere between 20- and 45-degrees of crank rotation, the trapped air/fuel charge is ignited by the spark plug and burning commences. At first, the process proceeds quite slowly (relative to subsequent crank rotation before TDC). A small bubble of fire expands gently away from the point of ignition between the spark plug's electrode and ground wire, and if all combustion were to continue at this pace it would hardly be completed in time for the following compression stroke. However, this small flame quickly heats the remaining mixture enough to enormously increase the rate at which burning occurs, and after the initial delay, the flame-front accelerates outward from its point of origin with ever-increasing rapidity—sweeping throughout the combustion chamber. And if the engine has been given the proper amount of spark advance, the piston will have just moved up to the top of its stroke as the rapid phase of combustion begins, so that the bulk of the burning is done while the piston is virtually stopped and the mixture compressed to minimum volume. By the time the crankshaft has rotated a few more degrees, and the piston is once again moving downward, the combustion process will have been almost entirely completed.

The preceding is what happens in the normal course of events; combustion does not always occur that neatly. The most common, regrettable combusion irregularity is detonation, the harsh knocking you hear just before an engine seizes, or melts a piston—and the noise you would hear, when running an engine on a dynamometer, as the needle on the scale begins an ominous retreat. Unhappily, the very process by which the mixture in the combustion chamber is pre-heated before its actual contact with the flame-front advancing from the spark plug, and rapid combustion thus made possible, is the process that may also lead to the sudden explosion of the combustion chamber's contents that we call detonation. Here's how it happens: It has already been noted that as the flame-front advances, the combustion chamber's remaining unburned mixture is heated, and this heating is caused not only by direct contact with the flame, but also by radiation and the overall pressure rise within the chamber. If the temperature of this remaining mixture is raised to its ignition point, all of it is consumed at the same instant in a single explosion. This explosion creates a shock, due to a fantastically rapid pressure rise, that strikes out against all its surroundings hard enough to make detonation' characteristic knock—and it is a shock with a force often sufficient to break the spark plug insulator's tip and damage both the piston and bearings. Even so, its worst effect is to force a lot of heat out into the piston, cylinder-head and the cylinderwalls. These are thus brought to abnormally high temperature, which tends to overheat the next air/fuel charge and make it detonate even more quickly and severely.

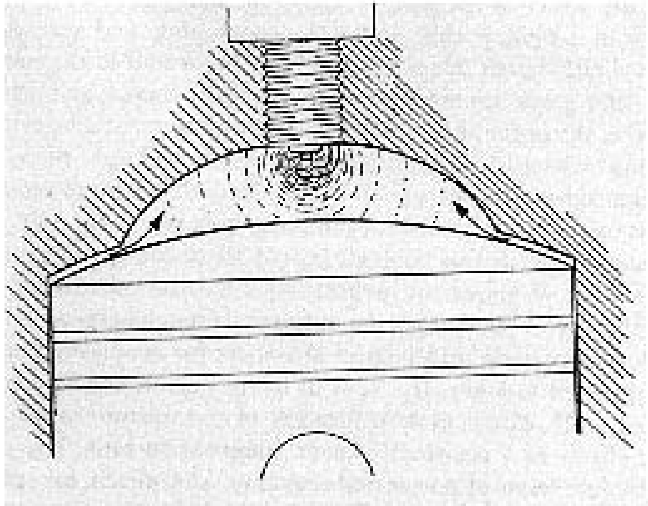
Should this detonation continue, it will overheat the engine's upper end to the point where ignition occurs before there is a spark: compression heats the mixture in any case, and when a lot more heat is added from the piston crown, etc., the mixture will be brought to "pre-ignite". Detonation has a



In this combustion chamber there is no squish band and the spark plug is offset. Detonation will occur when pressure, and heat radiating ahead of the flame front, cause the end gases to ignite.

very bad effect on power output; pre-ignition (thought by some to be the same phenomena) is even worse in that regard, but will not long continue unnoticed as it will very rapidly overload the piston – in both the thermal and mechanical sense – beyond the point of failure. Knowing that, you will appreciate that detonation is to be avoided if at all possible. One way to avoid detonation would be to simply hold the compression ratio to some very low number, as they would reduce the pre-combustion temperatures and thereby make detonation unlikely if not impossible. But that method is mostly (the exception I will deal with shortly) too expensive in terms of power-output efficiency. A better method is one employed in most engines today: use of a "squish" type combustion chamber, in which the mixture is trapped in a small pocket under the spark plug, and the rest of the cylinderhead surface over the bore is made to fit closely against the piston crown when the piston is at top center.

We have England's Harry Ricardo to thank for this type combustion chamber, which he created to cope with conditions that ceased to exist long before most of us were born. During the conflict that wracked Europe just after the turn of this century, there were not only shortages of internal combustion engine fuels, but the fuels available were of very poor quality – and would detonate severely in the side-valve engines of that period unless the engines were operated with a much-retarded spark, or their compression ratios



Combustion chambers with centrally located spark plugs and squish bands give a short flame travel in a compact mixture pocket; the end gases, being in thin layers, are too rapidly cooled to ignite.

lowered to about 4:1, or both. These measures had a terrible effect on fuel economy, naturally, and the problem led Ricardo to do serious research into the nature of detonation. We now know that the side-valve engine is particularly prone to detonation, as it of necessity has a very long combustion chamber. Ignite a fire at one end, and it will be a long while reaching the far corners of the chamber. In the interval between ignition and the completion of burning there is ample opportunity for the unburned part of the charge to overheat and ignite.

SQUISH BANDS

Ricardo solved the problem, once he had determined its nature, by lowering the underside of the cylinderhead in that part of the chamber over the piston. Thus, most of the mixture was concentrated right at the ignition source, and would be more likely to burn without detonating. The small part of the mixture caught between the cylinderhead's squish band and the piston was still subject to compression heating, but was fairly effectively shielded from radiation and was, moreover, spread in such a thin layer that it would resist ignition from any cause – as it would lose heat into the relatively cool piston and cylinderhead too fast to ignite.

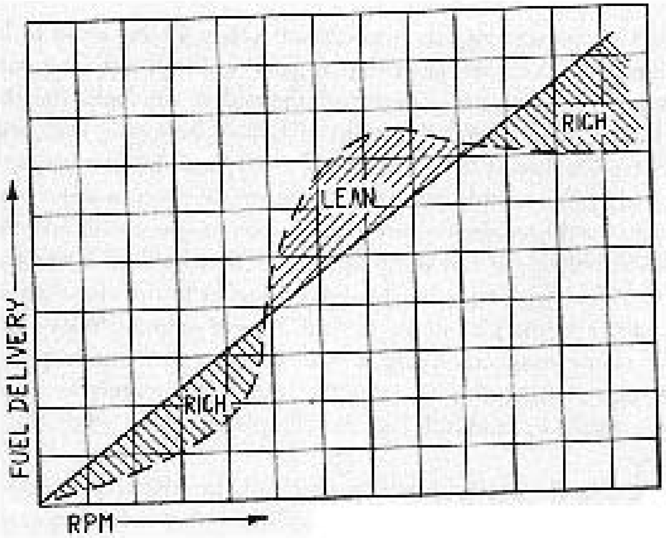
That still is the secret of the squish-type cylinderhead: It concentrates the main charge in a tight pocket under the spark plug, and spreads the mixture at the cylinder-bore's edges too thinly to be heated to the point of ignition. These "end gases" do not burn with the main charge, and are only partly consumed as the piston moves away from top center and releases them from their cooling contact with the surrounding metal. And right there is the disadvantage that comes with the squish-band cylinderhead, for mixture that does not burn is mixture that contributes nothing to power output. Of lesser importance, though only in this context, is that those end-gases contribute heavily to the release of unburned hydrocarbons out the exhaust pipe and into the atmosphere, and for that reason automobile manufacturers are now relying much less heavily on squish-band chambers for combustion control. You may be interested to know, too, that in many cases a non-squish combustion chamber, with its complete utilization of the mixture to offset the power-limiting effects of a necessarily-lower compression ratio, has proven to be best in absolute terms of power and economy. McCulloch, for example, make engines with both squish and non-squish cylinderhead configurations — having found that both have their applications.

Our application here, of course, is strongly biased toward maximum horsepower, and that points toward a squish-band head — which is what you will have in most motorcycles in any case. I will warn you, now, that it may be unwise to follow the old-time tuner's habit of increasing an engine's compression ratio as an opening gambit in the quest for better performance. Indeed, before your work is done you may find it necessary to reduce your engine's compression ratio *below* the stock specification. You see, in the final analysis it is not so much compression ratio as combustion chamber *pressure* that determines the limit – and these are not at all the same things. Your stock engine, with a carburetor size and porting chosen to lend it a smooth idle and easy starting, does a much less effective job of cylinder-filling than will be the case after it has been modified. More important, it will probably have an exhaust system that has more to recommend it as a silencer than as a booster of horsepower. These factors, in combination, make a very great difference between the cylinder pressures at the time of ignition in the stock and modified engine. Even given a certain willingness on your part to use a fairly cold spark plug — changing it frequently — and a further willingness to replace pistons and bearings more often in payment for added power, it may *still* be necessary to stay with the stock specification for compression ratio. Or, as I have said, to lower the engine's compression ratio from the stock condition. This last will be particularly true if you succeed in creating a much better than stock exhaust system.

By and large, you would be well-advised to ignore the whole business of compression ratios in favor of cranking pressures. There is, after all, a big

difference between the kinds of numbers you get by performing the traditional calculations to find compression ratio, and what is happening as the engine turns. My experience has been that you can use cranking pressures of 120 psi without worrying much about overheating anything. Maximum power will be obtained at cranking pressures somewhere between 135 and 165 psi. Going higher with compression, in a conventional motorcycle engine, can give a neat boost in low speed torque, but the thermal repercussions of higher cranking pressures will surely limit maximum output. On the other hand, fan-cooled kart engines perform very well at cranking pressures up at 200 psi, and water-cooled engines behave much the same.

One of the most undesirable side-effects that comes with too-high compression ratios is an enormous difficulty in getting an engine to "carburet" cleanly. When the compression ratio is too high, you'll find that an engine's mixture-strength requirement has a sharp hump right at its torque peak that no motorcycle carburetor can accommodate. You'll realize, after working with high-output two-stroke engines, that all of them are to some degree liquid-cooled — and that the cooling liquid is gasoline. It is true that an over-rich mixture tends to dampen the combustion process, and reduce power, but here again we find ourselves faced with the necessity for finding a balance between evils: We have overheating to rob power on one side, and we can cool the engine with gasoline, but too much fuel also robs power. The solution



Carburetors produce a mixture of nearly constant strength, but an expansion chamber's boost capability varies with engine speed and may alter the engine's mixture requirement above and below what the carburetor can actually deliver.

is a beggar's choice, in which we try to find the cross-over point between over-heating and over-rich mixtures.

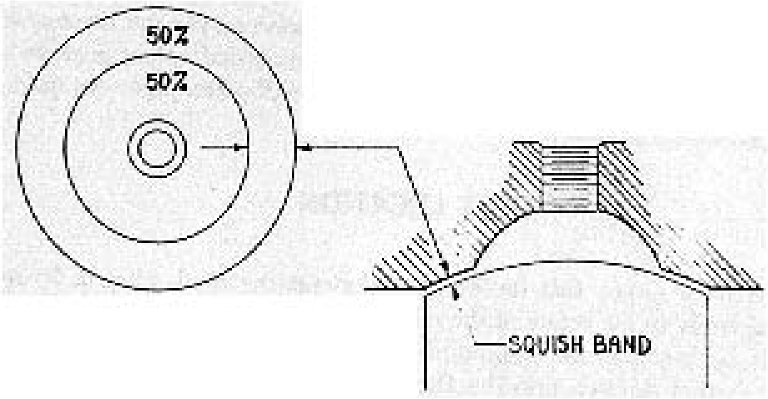
In an engine intended purely for road racing, with a torque peak virtually coincidental with its power peak and driving through a very close-ratio transmission (enabling the rider to hold engine-speed within narrow limits), making this beggar's choice is a fairly straight-forward proposition: you play with jetting until the motorcycle runs fast. However, road racing conditions allow you to stay right on the mixture-requirement hump; you don't have to worry about what happens two-thousand revs below the power peak, because that's below what you'll use in a race. Motocross racing is another matter entirely, and an engine with a mixture-curve hump will drive you absolutely mad. Jet a motocross engine so that it doesn't melt a piston every time it pulls hard at its torque peak, and (if its mixture-curve is humped) it will be huffing soot and losing power above and below that speed.

The answer to this problem is to iron out that mixture-requirement hump, because no matter how much work you do with the carburetor, it never will be able to cope with the engine's needs. All the carburetor knows, really, is how much air is moving through its throat, and it adds fuel to the air in proportion to the rate of air-flow; don't expect it to know when the piston is getting hot and respond by heaving in some more fuel. How do you get rid of the hump? You do it mostly by substituting a somewhat less effective expansion chamber: one that gives more nearly the same boost all the way through the speed range you are obliged to use by racing conditions, without any big surges. That will result in a drop in peak power, obviously, but you can compensate for it to a considerable extent with the higher compression ratio you previously were forced to forego in the interest of keeping the piston crown intact when the expansion chamber did its big-boost routine. Again, it is all a matter of finding the balance.

No matter what the compression ratio you ultimately use, it will have been influenced much more than you probably suspect by the combustion chamber configuration, and by certain gross characteristics of the head itself. Over the years, I have seen the fashion in combustion chamber forms swing back and forth, hither and yon, with first hat-section chambers in favor and then trench-type chambers, and torus-type chambers and so on and so forth *ad infinitum*. I was not, and am not, impressed. Combustion chamber form should be established with an eye toward only a very few special considerations, and these cannot account for even half the chamber shapes I have seen. Listed, though not really in order of importance, these are: surface/volume ratio; spark plug location; thermal loadings and combustion control. We will consider each of these in turn.

Surface to volume ratio is important because even in the part of the combustion chamber fully exposed to the advancing flame front, there will be a mixture layer adhering to the metal surfaces that does not burn. These layers, like that trapped within the squish band, are cooled by their proximity with the cylinderhead, or piston, and simply never will reach ignition temperature. And, like the end-gases from the squish band, they eventually find their way out the exhaust port, having taken no part in the conversion of fuel and air into horsepower. Thus, the best combustion chamber shape – taken strictly from the standpoint of surface/volume ratio – would be a simple spherical segment sweeping in a continuous arc from one side of the cylinder bore to the opposite side. No tricky changes in section, no squish bands, no nothing. And that is, in point of fact, precisely the shape employed in nearly all non-squish cylinderheads.

But if you want to use a true (measured from exhaust-closing) compression ratio much over 6.5:1, on a high-output engine, combustion control beyond that afforded by a non-squish cylinderhead will be necessary. Considerable variation is possible, but a good rule to follow is to make the cylinderhead's squish band about 50-percent of the cylinder bore area. For example, in a 3-inch bore – which has a total area of 7.07-inches^2, the squish band would be wide enough to represent an area of just about 3.5 in^2. Assuming that you have centered the combustion chamber proper on the bore axis, then your squish band would be a ring having the same outer diameter as the bore, and an inner diameter of just over 2-inches. The combustion chamber



Squish bands should constitute about half the cylinder bore area. Clearance between piston and cylinderhead should be held to a minimum to avoid effectively losing about 5% of the working mixture.