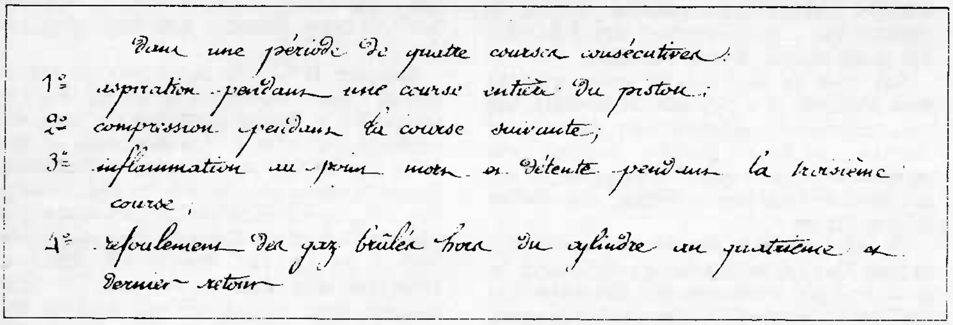
To be sung presto con marcato to a clatter of valve gear ...

Induction–Compression–Expansion–Exhaust

(or sometimes, more vulgarly, Suck-Squeeze-Bang-Blow

WE ARE OF COURSE ABOUT TO DISCUSS THE FOUR-STOKE CYCLE


Dans une période de quatre courses consécutives :
1° aspiration pendant une course entière du piston ;
2° compression pendant la course suivante ;
3° inflammation au point mort et détente pendant la troisième course ;
4° refoulement des gaz brûlés hors du cylindre au quatrième et dernier retour

BEAU DE ROCHAS, BREVET D'INVENTION N° 52.593/1862 (p. 31)

THE FOUR-STROKE cycle was conceived in 1862 by a Frenchman called Beau de Rochas in the words illustrated above, which we translate for the benefit of those who are not blessed with the gift of tongues:

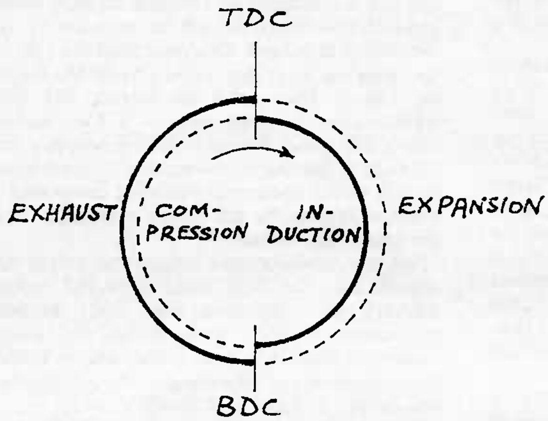
During four consecutive strokes:

1. *Inhalation during one whole stroke of the piston.*
2. *Compression throughout the following stroke.*
3. *Ignition at top dead centre and expansion during the third stroke.*
4. *Driving the burnt gas out from the cylinder during the fourth and last stroke.*

These four events, abbreviated formally (and even occasionally sung) as "Induction, Compression, Expansion, Exhaust", and rather more vulgarly as Suck, Squeeze, Bang, Blow, will be the concern of this article.

Discussion of the four-stroke cycle can conveniently be divided into two areas – why the modern cycle does not exactly follow the simple rules given by Beau de Rochas, and, how the processes involved are achieved in practice. These two areas overlap, as we shall see, but in this article we talk about the cycle of operations itself, starting at top dead centre at the beginning of the inlet stroke.

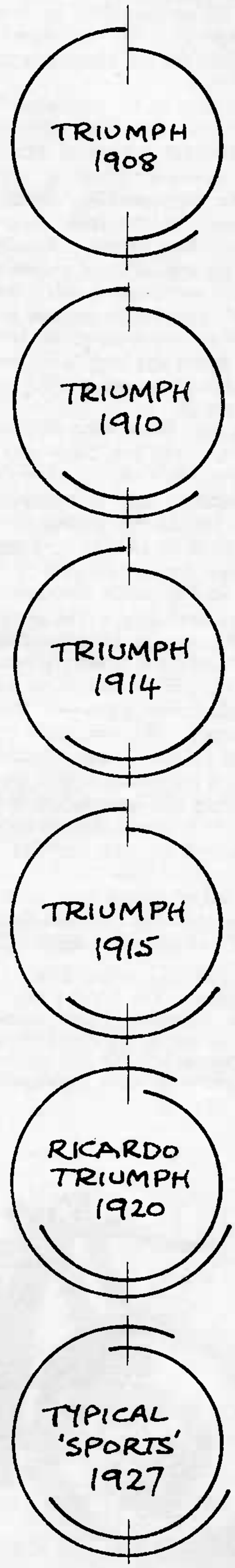
The piston descends, increasing the space in the cylinder, and atmospheric pressure forces mixture into this space to fill the partial vacuum formed. When the piston reaches the end of its stroke, the inlet valve should close, but if this happens the gas rushing along the inlet passage will "pile up" against the now closed valve and then bounce straight back out through the carburettor. This is bad in two ways – the power output is limited because the cylinder doesn't really fill properly and the gas which bounces back out wastes valuable fuel. With a bit of cunning we can avoid both these faults; if we delay closing the inlet valve until the piston has started back up again, the gas will continue flowing for a brief period into the engine under its own inertia, after which the valve should close, trapping tne extra gas. This looks as though we are poaching useful movement from the compression stroke, but by this trick not only can we prevent blowback but also cheat slightly more than a cylinderful of mixture into the cylinder, giving more power, because during the rest of the compression stroke proper the piston is compressing a decent dollop of mixture.

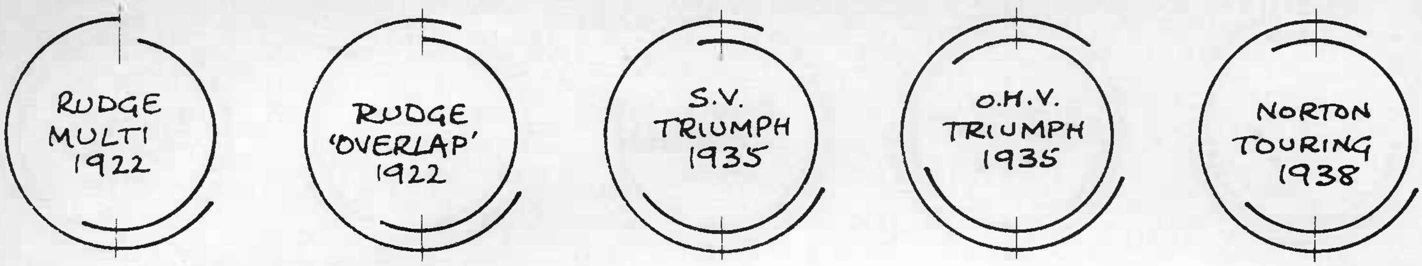


THEORETICAL VALVE TIMING
BEAU DE ROCHAS 1862

Ignition is due to occur at the point of maximum compression, according to the formula, but in practice again we bend the rules. If the mixture could all be burnt in no time at all, top dead centre would in fact be too *early* to ignite it, because maximum pressure would then be on the top of the piston when it could exert no turning force on the crankshaft. What we need, rather, is maximum pressure exerted just after TDC, so that none of the effort is wasted trying to push the crank straight out of the bottom of the crankcase yet there is plenty of piston movement remaining to provide the expansion and the power we need. This is more difficult than it sounds because it is not possible in practice to burn the mixture instantaneously (and if it were, the enormous shock would destroy a conventional engine, but that's another story). Rather, it takes quite a long time, relatively speaking, for burning to be completed, and this "slow" pressure rise means that we must ignite the gas some time before the point when maximum pressure is intended to occur.

For Dr Nickolaus A. Otto, who gave his name, in England but strangely not in his native Germany, to the cycle of events which he made famous, top dead centre was a suitable place to start ignition (although he did it by chopping off a slice of a separate flame and feeding it into his cylinder!) His engines only rotated at a maximum





of 200 rpm so he had a sixth of a second for each stroke.

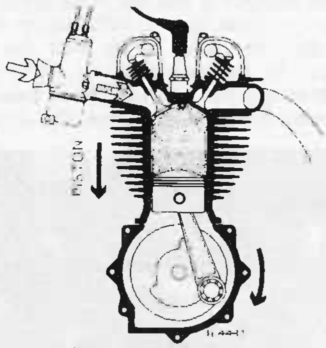
His assistant Gottlieb Daimler made engines rotate at 900 rpm, which would have required earlier timing, but his ignition was by hot tube and therefore the exact firing point was very difficult to measure, or even to predict.

As engines achieved higher and higher rotational speeds ignition timing grew earlier and earlier, until in the 20s the better understanding of combustion, and therefore of combustion chamber design, raised the speed of burning to something like its modern level, and timings settled down to around 35° before top dead centre at high speed. At lower engine speeds, below about 3,000 rpm, less advance is needed because there is more time available for burning; if the same settings are used at low speeds maximum pressure may well occur before top dead centre, forcing the piston back down the bore and turning the crank backwards. This fact will not have escaped the attention of readers who are also VOC members, and even one or two Yamaha owners. A mechanical device is normally used to vary the timing manually or automatically – typical slow-running timing is around 10° before TDC.

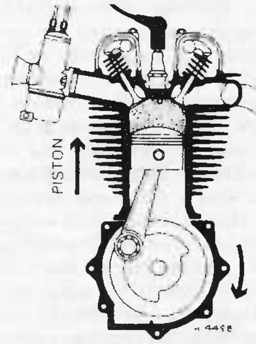
Back to the mixture, now blazing away and forcing the piston down on the expansion stroke. At bottom dead centre no further useful expansion is possible, so the exhaust port opens to allow the burnt gas out. That's what was intended, but we can improve on this, too. Certainly we can only get maximum useful expansion by leaving the exhaust port closed until BDC, but then during the whole of the next stroke the piston must *force* out the old gas, and at least to start with this gas is at high pressure, so quite a lot of the benefit of the expansion is used up in clearing the decks for the next bit of action. This is especially true if we use a conventional poppet valve which for simple mechanical reasons cannot open instantaneously so the rising piston has to work against high pressure until the valve opening is wide, and the loss this involves is considerable.

What we can do to avoid this loss is to open the exhaust port early, so that the last bit of expansion serves to force out the exhaust rather than force down the piston. Gas pressure during the last bit of the stroke is not much help anyway because towards bottom dead centre the piston simply hasn't got very much further to go. This early opening of the exhaust port, then, enables the main bulk of the exhaust gas to be blown out by the pressure still remaining when the gas has expanded, and during the exhaust stroke proper the piston rises against a pressure only slightly above atmospheric.

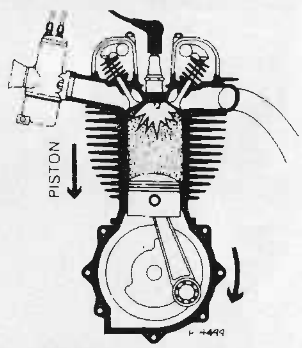
At top dead centre the exhaust valve should close, but again we alter the original intentions. There is always a combustion space above the piston at top dead centre, and at the end of the exhaust stroke this space will still be full of combustion products. New mixture drawn in during the next stroke will be diluted, thinned out, cluttered up with spent old gas, which means not only that we don't get as much new mixture in as we could, but that the burning of the contaminated mixture is slowed down by the old gas getting in the way. The time available for the complete burning of the mixture is desperately short; at 10,000 rpm there is only 0.003 seconds for the whole expansion stroke, so we must not have anything slowing combustion down, or



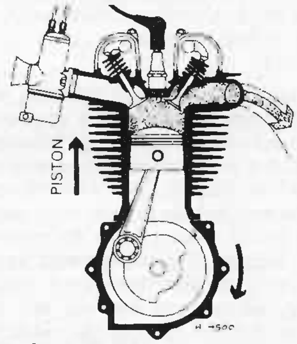
1 INDUCTION



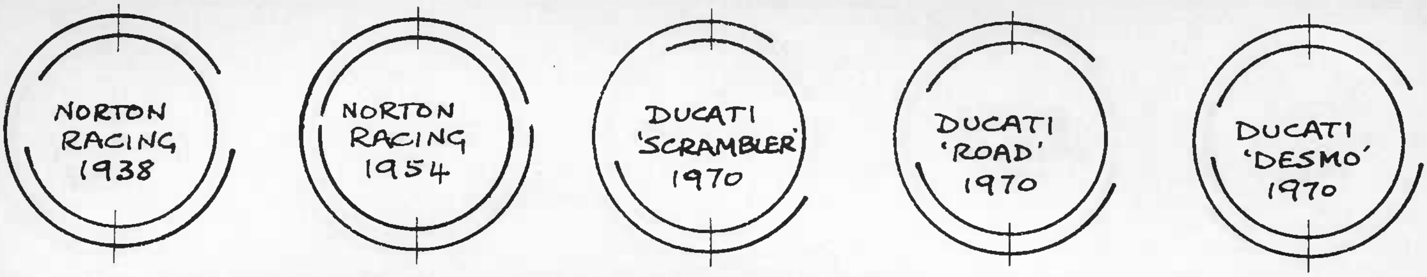
2 COMPRESSION



3 POWER



4 EXHAUST



much of the power will go blazing away down the exhaust pipe.

Until the 20s this was what usually happened, as combustion was not understood properly and timing, based on slow-moving gas engine practice, followed the theoretical cycle fairly exactly. How then can we sweep out the debris left at the end of the exhaust stroke?

This sweeping out, or scavenging, as it has become called, is done by messing about both the exhaust and the inlet timing. At the end of the inlet stroke we left the valve open rather longer than theory suggested so that the inertia of the rapidly moving gas stream would continue to cram in mixture while the piston started to rise. Here we can do the same thing; we leave the exhaust valve open a bit longer than we "ought" to, and use the inertia of moving exhaust gas whistling down the exhaust pipe at perhaps 300 or 400 mph to draw out as much as possible of the dregs of combustion. However well this works it cannot work perfectly – nature abhors a vacuum as much as she always did – and there are still traces of burnt mixture about, which we can only get out by replacing them with something else. This is the really cunning bit; we allow the inlet valve to open early, before top dead centre, so that new mixture can be drawn into the combustion chamber *by the escaping exhaust,* not only allowing all the wicked old gas to be removed but starting the lovely new mixture moving into the cylinder before the piston starts on its way down the bore.

Several real advantages result from this period of "overlap", when both valves are open around TDC. The exhaust is swept out thoroughly, making sure that the next combustion is as quick and effective as possible. The new mixture is started on its way into the cylinder early and this longer inlet period enables us to get more new mixture in. Mixture is also persuaded into the cylinder by using the otherwise wasted energy of the escaping exhaust gas and not the stored energy of the flywheel drawing the piston back down the bore. Just as it is wasteful for the piston to rise against high pressure on the exhaust stroke, a descending piston which has to work against a partial vacuum must be provided with power from somewhere, so the more gas we can seduce into the combustion space by some other means the less the flywheel will slow down on the inlet stroke.

Finally, in poppet valve engines at least, the exhaust valve is always the worst overheated part of the engine, so under really adverse conditions it can be useful to allow an engine to be "over-scavenged" – to allow not just the exhaust gas but a bit of cold new mixture past the exhaust valve. This is a waste of fuel but in the prodigal world of racing, of sprinting, even of motorcycling in general, it is often a useful way of preventing overheating of a component which is very difficult to cool otherwise. If the exhaust valve does run too hot, this can cause the end of the valve to fall off, disastrous enough as an extreme case, but even before the temperature rises high enough to cause mechanical failure the red hot valve head can ignite the compressed mixture before the proper spark occurs. This pre-ignition, not desperately harmful in itself, leads on to detonation, the real villain on the petrol engine scene which can destroy as much of the engine as a broken valve but in a much more insidious way.

To summarize the developments, both valve opening periods are extended at each end to give greater engine performance. Early opening relieves the piston of much of the arduous and power-absorbing duties of induction and exhaust, and late closing enables us to take advantage of the inertia of the gases to complete the processes more thoroughly.

The amounts of lead and of lag which are ideal depend on many factors, including the size of the cylinder, the layout of the inlet and exhaust valves, the size and shape of the combustion chamber and the inlet or exhaust passages, the fuel used, and the engine speed. The settings used in practice are therefore inevitably a compromise and although, as we have seen, the point of ignition is normally varied, any attempt to make valve gear with variable timing has been fraught with difficulties. With fixed timing of the opening and closing of the valves, there is inevitably some lack of efficiency at extremes and this helps to explain why the flat-out performance of road-going machines designed as a reasonable compromise can sometimes be improved by fitting a camshaft with more extreme timing, and why the touring performance with such a camshaft makes you wonder whether it was really worth it.

Next month we will see how all this theory is put into practice, how valve gear has developed since the primitive brave designs of Otto and Daimler, enabling engine speeds, power-to-size and power-to-weight ratios to rise one hundred fold – but, surprisingly, efficiency to rise less than one hundred per cent.

T.R.S