Knock, knock...

Kevin Cameron

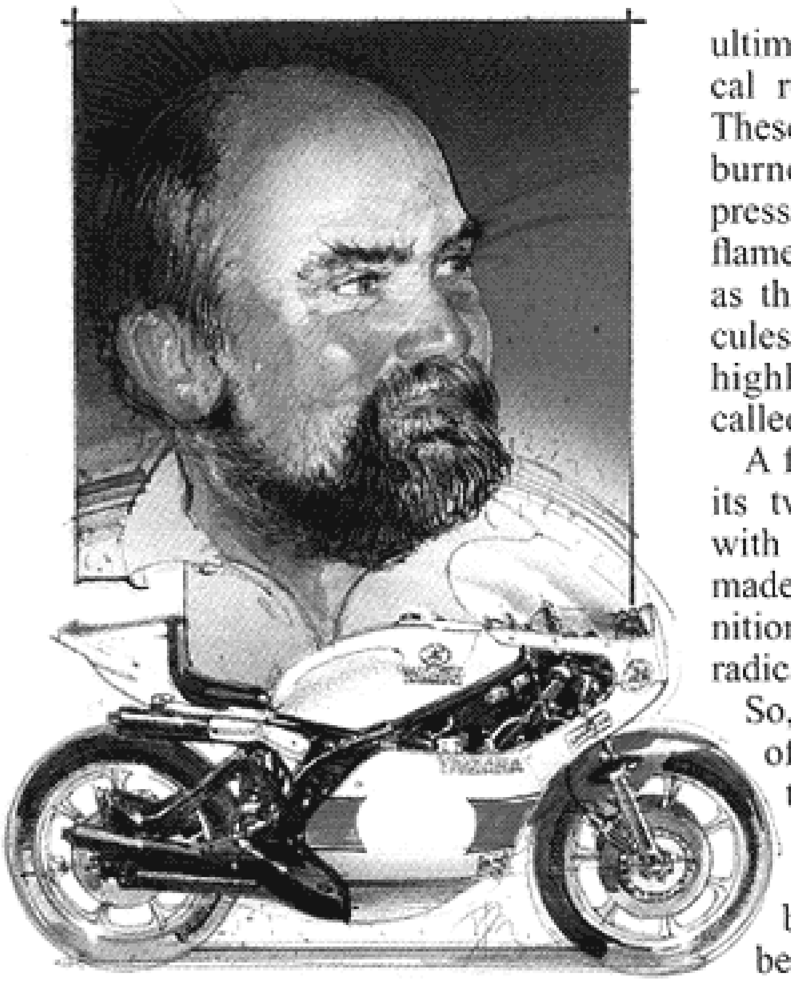
DR. RUDOLF DIESEL REALIZED MORE than a hundred years ago that a high compression ratio was the key to high power with low fuel consumption. Yet the gas- and liquid-fueled internal-combustion engines that were becoming common in his youth could not operate at high compression without terrible knocking and engine damage.

It took a while to figure out what was happening. Some believed the problem was pre-ignition–firing of the charge before the spark by contact with hot carbon deposits or residual hot gas. Yet even freshly assembled engines, operated with every care to eliminate hotspots and residual gas, would knock on a high compression ratio.

Harry Ricardo discovered that different fuels would knock at different compression ratios, showing that knock was related in some way to fuel chemistry. At first, fuels were rated according to a Highest Usable Compression Ratio, or HUCR. This concept broke down because this ratio was different for different combustion-chamber shapes. Evidently knock depended upon fuel chemistry and chamber shape.

Ricardo found out that the more rapid the combustion, the less likely knock became. Combustion-chamber turbulence had a strong effect on flame speed, so Ricardo made his famous "turbulent head" for sidevalve engines (ones having its valves located in the block, to the side of the cylinder bore, as in most lawnmower engines). In this engine, the combustion-chamber volume was mainly located above the valves, with the rest of the chamber being very close to the flat piston top at TDC. As the piston approached on its compression stroke, the mixture trapped between piston and flat-topped cylinder head was rapidly squirted out into the main chamber above the valves. This rapid charge motion greatly accelerated combustion. Engines with this type of head were able to run, detonation-free, at much higher than normal compression ratios. Normal in this period was about 3:1.

At such low compression ratios, an increase of a full number gives a big increase in torque, so Ricardo's turbulent head was a real improvement. In this country, it allowed Flatheads to outperform the legendary eight-valve factory ohv board-track engines of the time.



If fast combustion allowed engines to run with higher compression, then a third variable had to be added to detonation's causes: Time. Confirmation of this idea came from the fact that, in general, knock was worse in larger-bore cylinders. It took longer for flame to consume a larger chamber.

Dr. Graham Edgar knock-tested a long list of pure hydrocarbons in the 1930s, showing that certain chemical structures resisted detonation better than others. This led to the octane number scale, a system for rating the anti-knock behavior of fuels on a scale of 0-100. It revealed how better fuels could be created by blending either appropriate pure substances or particular refinery streams into gasolines. At General Motor's Delco Lab, Thomas Midgley ran thousands of tests with a roomful of engines, searching for some compound that, when mixed with gasoline, could prevent or control knock. After some false starts, he discovered the amazing anti-knock action of tetra-ethyl lead. One gram of this extremely poisonous liquid, added to a gallon of gasoline, raised its octane number several points. The ensuing switch to leaded fuels made practical the much more fuel-efficient high-compression engines of the later 1930s. The combination of especially knock-resistant hydrocarbons, such as iso-octane, with lead, made possible a tripling of the power of aircraft piston engines from 1935 to 1945.

Later, it was discovered that knock's ultimate cause was heat-driven chemical reactions in the fuel-air mixture. These occurred as the remaining unburned mixture was strongly compressed and heated by the approaching flame front. These pre-flame reactions, as they were called, broke fuel molecules apart, causing the formation of highly reactive chemical fragments called active radicals.

A few years ago, Honda showed with its two-stroke EXP-2 rally bike that with proper control, engines could be made to run smoothly without spark ignition, from the effect of these active radicals alone.

So, knock results when the population of active radicals in a region of mixture rises above a certain level. At this point, the unburned mixture remaining at the edges of the combustion chamber ignites by itself, before the normal flame front can reach it. This mixture, chemically altered by pre-flame reactions into a sensitive explosive, now burns at the local speed of sound. As this is at very high temperature, the resulting fast-moving pressure front can do real damage. Light detonation scours away the heat-insulating layer of stagnant gas that normally protects piston and head from combustion heat. Prolonged heavy knock softens and erodes pistons, causing seizure or punching holes through the domes.

Without lead, fuel octane ratings are now maintained by increasing the use of knock-resistant ring-structured aromatics like toluene, and branched chains like iso-pentane and iso-octane. Before lead was removed from pump gasoline, aromatics made up about 20 percent of the fuel. Today, gasolines typically contain twice that percentage.

Around 1964, Honda discovered that if an engine revs high enough, its mixture turbulence and combustion speed are rapid enough to "outrun" detonation. This causes an engine's octane requirement to decline steadily as it revs beyond 12,000 rpm. This effect is extensively exploited in Formula One, and will become important at the high revs of the coming era of four-stroke Grand Prix bikes. Current fuel rules for F-1 and World Superbike appear to limit octane number, but since standard tests are conducted below 2000 rpm, it's obvious that an effective octane number at, say, 15,000 rpm could be quite different. ◘