High Compression

By David Vizard

--Whether a low buck racer or an almost over financed team, compression has many race winning attributes you should know about.

When power on a budget or absolute maximum power is needed a suitably high or ultra high (above 13.5/1) compression is, as often as not, the primary key to success. Certainly the subject of compression is not to be taken lightly. Nor is the fact that C.F. Taylor, in his landmark work 'The Internal Combustion Engine', shows graphed test results indicating that gains tail off to virtually nothing at 17/1. These results are often quoted as an argument against pushing the compression to such limits. Such an argument is based on the grounds that increased unreliability from cylinder pressure and a very real possibility of detonation offsets the *supposedly small gains* to be had.

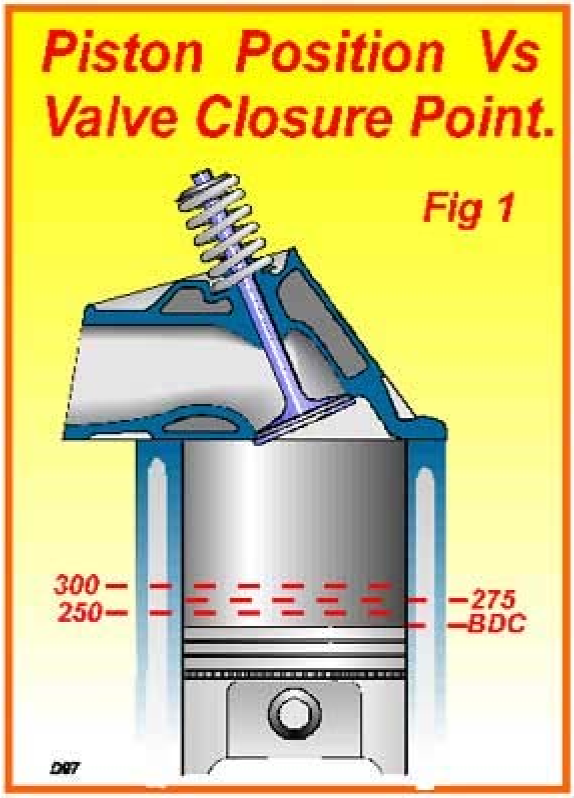
Unfortunately this is only half the story. Having presented this graph Taylor goes on to say that this was done on a production motor (which would have had a short cam) and that many variables, including adverse chemical reactions during combustion, played a part in the results seen. He also states, in so many words, that a great deal more work needs to be done in this area. It's the last part of Taylor's observations that are so often left out of any argument as to the pros and cons of ultra high compression. Over the last 20 years the effects and interactions related to high compression ratios have been intensely explored in an effort to maximize the output from normally aspirated drag race motors. Applying the wealth of this work can easily make the difference between winning and being an also ran.

Before arbitrarily deciding on the compression you want for your motor consider that what you might like for compression is actually irrelevant - it's what the motor wants that counts. Just how much can usefully be used depends on a variety of variables which will be detailed shortly. *What is not commonly appreciated is how much power and torque can be sacrificed by not giving sufficient thought and attention to maximizing a motors CR.*

In almost all circumstances the higher the compression ratio the greater the output of the motor. Striving to maximize this can pay big dividends as demonstrated by the pushrod 500-inch (8.2 liter) carburated 2 valve per cylinder ProStock Formula drag race motors. With CR's of around 17/1 these motors are developing close to 1300 hp (150 hp plus per liter) and upward of 820 lbs.-ft of torque (100 lbs.-ft per liter). A reasonable estimate indicates that something well in excess of 100 hp of this impressive output can be attributed to the effective utilization of the ultra high ratio's involved. As we shall see shortly that does not mean just arbitrarily upping the CR.

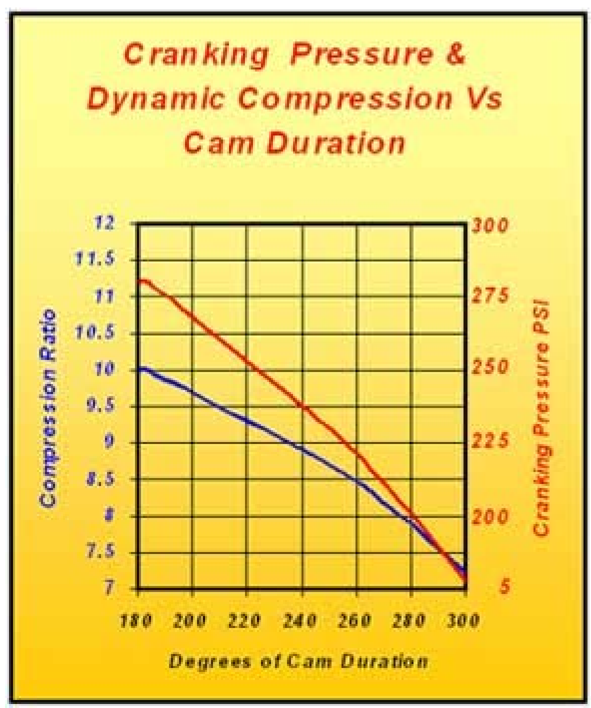
At this point we will make a start with those factors which, in conjunction with a change in CR, have a large effect on power. From here we will work our way down a list.

Intake Valve Closure to Compression Compatibility.



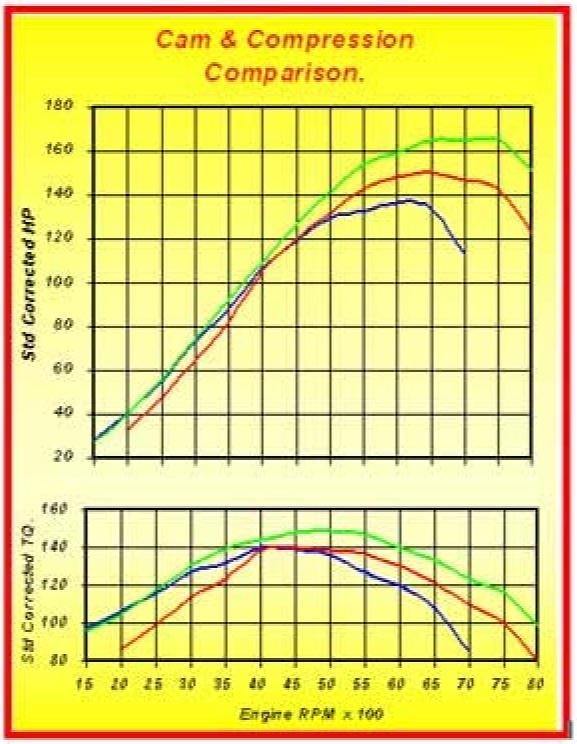
There is a certain minimum functional CR for any given cam duration. *If the CR drops below this minimum it proves better to choose a cam of less duration, as it will make more HP.* This is one of those parts compatibility factors so often mentioned by the popular press but rarely if ever, actually defined.

The point at which the intake valve closes after BDC is dictated mostly by opening duration and to a lesser extent by the cams Lobe Centerline Angle (LCA) and it's advance. In simple terms the more opening duration the cam has the further the piston is up the bore on the compression stroke. This means at low rpm less air is trapped above the piston prior to valve closure. This in turn reduces the effective CR. Fig 1 shows the piston position for three typical small block Chevy cams each of successively longer duration. Starting at a 10/1 ratio the graph Fig 2 shows the extent of the drop in effective compression ratio and cranking pressure as the cam duration is increased. Just how much effect this can have on output is clearly shown by the tests done with a 2 liter Pinto motor (Fig 3). This unit has almost identical response characteristics to a small block Chevy so a direct percentage comparison can be made between the two.



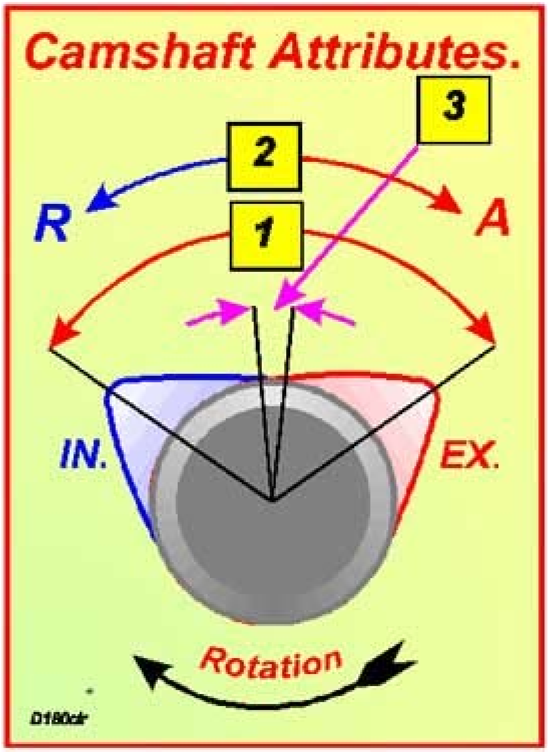
The blue curves are for a production cammed 9/1 2-liter motor equipped with a ported big valve head, side draft 45 Webers and a 4 into 2 into 1 exhaust system with muffler. Installing a 285-degree duration (at seat) cam with no other changes reduced the low speed torque (red curve) with parity not being reached until close to 4000 rpm. Above this the 285-degree cam (some 30 degrees longer than the production cam) paid off. At peak power about 13 additional hp was realized. On the negative side the motor would not take full throttle below about 1800 rpm as doing so would cause it to cut out completely.

For the tests shown by the green curves the compression was raised to 11.5/1. This brought the cranking pressure up to about 7% higher than was seen with the production cam and 9/1



CR. The biggest gains seen were at the low end. With 11.5/1 the motor could be pulled down to 1500 rpm where it made only 1.5 lbs.-ft less torque than the stock cam/compression combination. By pairing the cam duration with an appropriate CR peak power increased by 26 hp with virtually no low speed penalty.

LCA to Compression Compatibility.

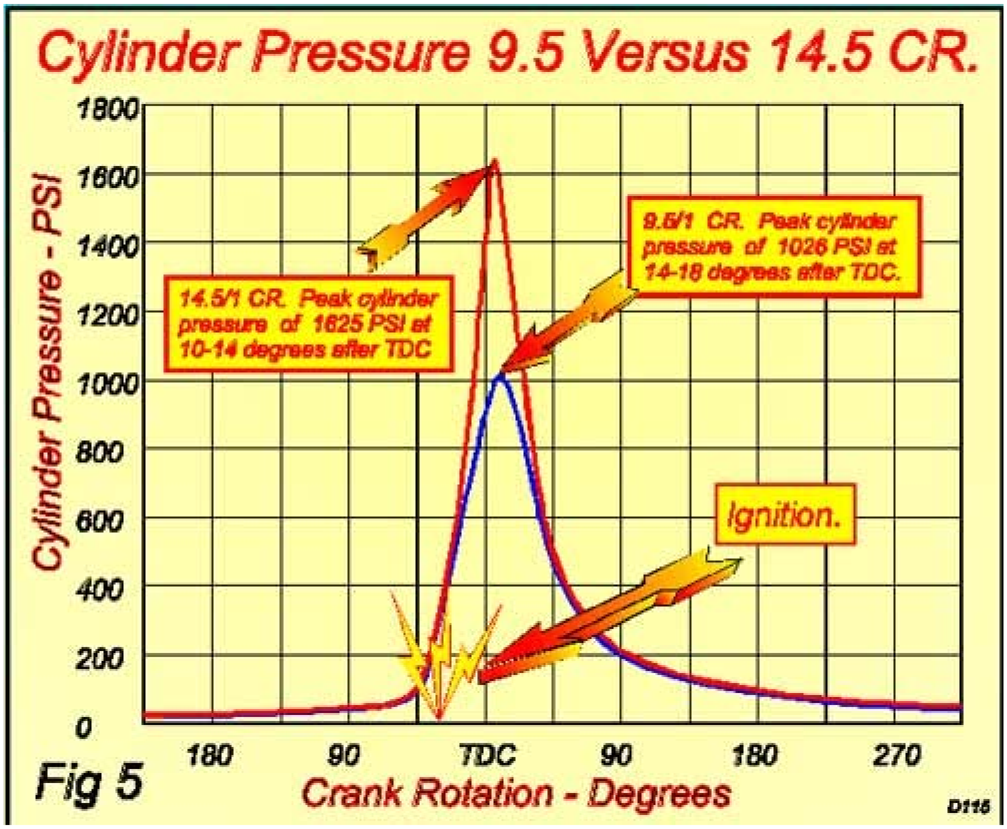


Although it is the most influential factor the intake valve closing point is not dependant on the opening duration alone. Although less significant the Lobe Centerline Angle (LCA) and the cam advance also influence the intake valve closure point. (see Fig 4 for details). Except for rare occasions when advance or retard is substantial (more than about 4 degrees) the interaction between LCA and compression is by far the most important. The bottom line here is that cams with wider LCA's (numbers getting larger) respond to an increase in compression to a greater extent than those with tight LCA's (numbers getting smaller). The other side of the coin here is that the higher the compression ratio used the wider the optimal LCA becomes. For instance a 500 inch 17/1 CR motor with intake valves around 2 ½ inches produces best results with a LCA of about 113 -114 degrees. Drop the compression to 13/1 and the optimum LCA will tighten up to 110-111 degrees. This piece of info can be very useful as building ultra high compression motors almost inevitably brings about a piston to valve clearance problem at TDC on the overlap cycle. Knowing that the LCA can be spread and the overlap reduced as a consequence means that the potential for valve to piston interference is measurably reduced.

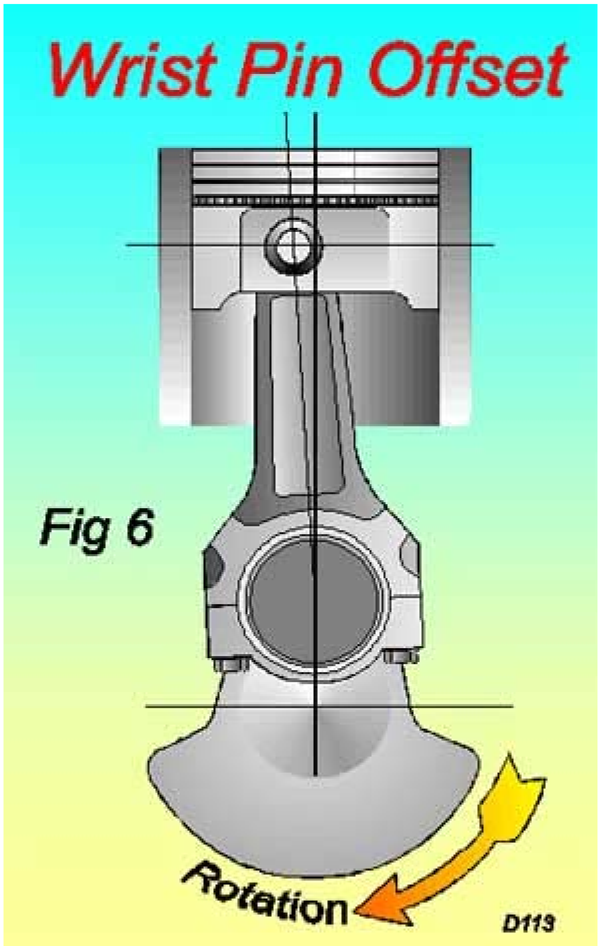
Cam Advance & Compression Compatibility.

Due to a great deal of dimensional and proportional commonality, most 2 valve motors with parallel valve configurations produce best power curves with about 2-4 degrees of advance. The more advanced the cam is the earlier the intake closes. This leaves the motor a little less sensitive to the compression/valve closure timing combination. If a motor makes more HP with the cam retarded then there are two issues to deal with. The first and maybe the least important is the fact that the motors output will be more sensitive to compression and valve closure timing. The second is that there may be a problem with the motors basic spec as retarded cam timing is rarely optimal other than in motors with extremely good low lift intake flow such as seen with 5 valve per cylinder units.

CR and Cylinder Pressure Decay.



When the compression ratio is raised peak cylinder pressures follow suit. A basic rule of thumb is that peak pressures will be approximately 100 -110 p.s.i. for every ratio. A 10/1 ratio motor will typically see 1000-1100 p.s.i. peak pressure. A 16/1 motor will be between 1600 and 1760. An ultra high CR then means big pressure numbers. This puts a lot of stress on gaskets, rods, cranks and blocks. Fortunately modern metallurgy and engineering is up to the task of dealing with the situation. Probably the most demanding area has been in the field of head gaskets but progressive companies such as FelPro have stayed on top of the situation.



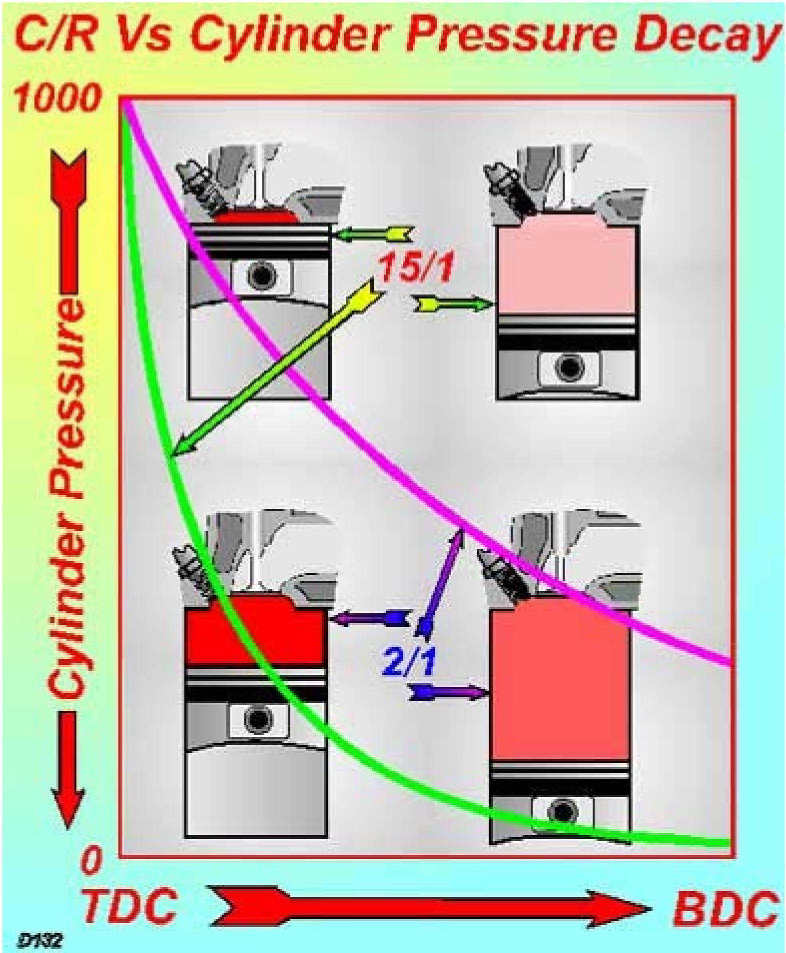
Apart from the increase in peak pressures there are other factors which are useful to know about. The first is that the higher the CR the earlier peak pressures occur in the power stroke. A 10/1 motor may reach it's peak pressure about 14 -15 degrees after TDC where as a 13/1 motor would, all else being equal, experience peak pressure at 12-13 degrees and a 16/1 motor could be as early as 10 degrees (Fig 5 shows a typical situation) With such high peak pressures occurring so close to TDC the angle of the rod and crank become more important. At such high compression ratios there is more to be gained from offsetting piston pin bores or preferably offsetting the bore itself to increase leverage on the crank.

The validity of offsetting the piston pin becomes even greater when the rate at which cylinder pressures decay is taken into account (Fig 7). Essentially the rate of pressure decay is faster in the high compression cylinder. This means more of the work is applied to the crank earlier in the stroke and less later. Since rod and crank angles are not as favorable early in the stroke what we do with them becomes more important. To more easily understand this aspect it is best to consider the expansion ratio (ER) rather than the compression ratio. Numerically these two are the same. The difference is that the CR is when the piston travels up the bore to TDC and the ER is when it travels down from TDC. The fact that the pressure decays faster when higher CR's are used is due almost entirely to the geometry changes brought about by the change in the CR. Fig 7 shows how the pressure decays due to the volume increasing faster the higher the compression.

What Happens Around TDC When the CR is Raised.

Appreciating the effect that the interaction of cam and compression have on a motors power curve are relatively easy to see. These interactions all take place as a result of the valve closure point and the compression. There are however a number of other lesser factors which are no less of important in the search for maximum output. These factors relate to how raising the compression affects various aspects and events in and around TDC during both the overlap period and the power stroke.

During the overlap period a higher CR reduces the exhaust dilution of the incoming charge. A lot of this is due simply to the fact that the smaller chamber contains less exhaust. But additional effects, which improve scavenging, also play a part. Assuming the exhaust to be effective a higher compression ratio causes a small, but significant increase in exhaust velocity while the piston is in the vicinity of TDC. The smaller chamber and increased exhaust velocity play an important role toward bringing the motor up on the cam sooner and making those big low-end



gains seen. Just after TDC the cylinder pressure can be measurably lower. This encourages an earlier and slightly greater inflow into the cylinder. The higher exhaust velocity helps ensure that it is fresh intake charge that is entering the cylinder rather than undesirable exhaust returning from the exhaust port. This last factor also contributes toward a reduce intake charge temperature which again benefits output.

When race regulations call for an intake restriction, such as a two-barrel carb on a V8, chamber scavenging becomes significantly more critical. When an intake restriction exists, there is a greater tendency for the motor to pull exhaust gases rather than intake back into the cylinder. For this reason maximizing the combined effect of reduced chamber volume and increased exhaust velocity and a slightly cooler intake charge are important factors toward increased output. Although influenced by the effects of exhaust length tuning we see that as the CR is increased there is a tendency for the VE to marginally drop below peak torque and increase after peak torque.

Gains on Carburated V8 Motors.

If your motor is a carburated V8 with an open plenum, race style intake manifold and a single 4-barrel carb, raising the CR has important implications other than the cam/CR issue discussed earlier. At low speed, big cfm carbs tend to deliver poorly atomized fuel and metering accuracy, along with fuel distribution, also suffers. A long duration cam aggravates this situation. Not only is the cam less able to deliver low speed results in its own right but it reduces the carbs ability to do it's job. At low speed a bigger cam reduces the breathing efficiency of the motor because no pressure wave tuning or inertial ramming of the cylinder takes place. This means the airflow demand made on the carb is reduced. To the carb this seems as if the motor it is servicing is smaller than it really is. In effect this produces the same effect as having a carb too big for the job. When the CR is raised the start of the induction stroke and the pulse it communicates to the carb via the intake manifold is much more pronounced. This increases the booster signal, which in turn improves atomization and metering. In addition to this the higher compression produces a higher charge temperature toward the end of the compression stroke thus causing more of the fuel to vaporize. These last points represent some especially good reasons why carburated alcohol burning motors should have ultra high CR's.

The aspects of increased compression just discussed considerably improve the low speed combustion process. A point to make here is we are not talking peanuts. Getting the cam and compression right along with adequate carb booster signal can be worth, on a typical 350 inch V8, 60-80 lbs.-ft of torque in the 1500 to 3000 rpm range as well as a good chunk of power the rest of the way up. To put the low speed improvement into perspective that's like adding 50 inches to the motor's displacement.

Other Points of Relevance.

When the CR is raised the increase in power is largely due to the fact the thermal efficiency is improved. By considering the expansion ratio as shown in Fig 7 it is easy to appreciate that more energy is extracted from the charge. (i.e. the biggest difference between starting and finishing pressures). Other than increased output, and equally significant, is improved fuel economy, especially under part throttle driving conditions that increased compression brings about. This last aspect is an important issue for the street performance enthusiast. Raising the CR and using a more expensive, higher octane fuel can often prove no more costly per mile because the increased economy can partially and sometimes completely offset the greater fuel expense. This is especially the case if the substantial increase in low speed torque allows a torque converter with a lower stall speed to be used. In such instances this means being able to enjoy the additional power without necessarily incurring greater fuel costs. In one instance I ran a 13/1 motor on premium and octane booster. Allowing for the improved mileage brought about by a) the higher compression and b) the tighter converter I estimated that running on additized premium fuel was costing me no more per mile than less compression and a looser converter to compensate for the lesser low speed torque. So, for no increase in running costs, the higher compression and tighter converter meant I was able to enjoy the benefits of a 515 hp 350 instead of one of about 470 hp.

More on the minor side is the fact that increasing the CR cuts heat loss to the coolant. In addition to this the exhaust temperatures drop by about 20-25 F per ratio increase. Also the exhaust valve temperatures drop so, all else being equal, exhaust valves have less, not more, tendency to burn out.

Maximizing Compression for a given Fuel Octane.

Increasing the CR to the limit always brings the issue of detonation into the picture. Fuels having octane values as high as 115 are usually good for more than can physically be built but many classes of competition regulate the fuel that can be used to 100 octane Research (RON) or less. The challenge then becomes one of finding ways and means to make the most of the octane available. The key here is maximizing the use of every octane number available. Since the octane number required increases at the rate of about one whole number for every 21 degrees F increase in air temperature our first line of action is to keep the induction system as cool as possible.

Drawing air from a cool source outside the engine compartment is typically worth the equivalent of two whole numbers. Intake manifolds with any kind of heat are out and isolating the intake from exhaust and block heat is worth the effort. Thermal barrier coating of the intake tract has proven to be worthwhile on every motor we have tested on. The last component the incoming charge meets is the intake valve. This is subject to greater heat input than the exhaust valve because of it's significantly greater area. Coating the chamber face of the valve is simple to do and worth the effort.

Still on the subject of valves the temperature the exhaust valve runs at can often be the prime factor limiting the compression that can be used prior to the onset of detonation. To that end there are definite advantages to using sodium cooled exhaust valves.
Last on the thermal do's and don'ts list and about the most obvious is to use a cooler running thermostat. For most applications coolant temperatures should not exceed 170 F (77 C). Above this temperature the typical high performance motor will start to loose power and it's octane requirement will go up. An interesting point that ProStock engine builder Jim Yates made during his '98 lecture at the Superflow conference was that his 17/1 ProStock motors ran temperatures of only about 130 -140 F.

Swirl.

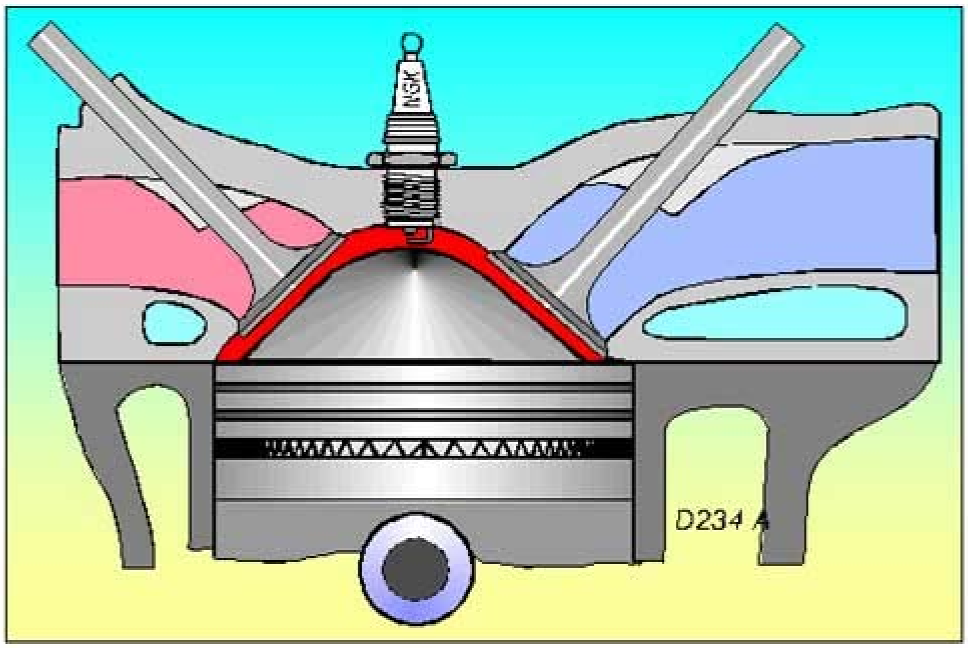
In addition to keeping the intake tract cool the port form itself is also an influence. If a strong swirl action can be generated without loss of flow (not always easy) the combustion process will be more consistent from cycle to cycle and the burn rate faster. With a faster burn rate the end gases are exposed to the advancing flame front for less time so are less susceptible to detonation. Additionally fast burn chambers, although having a higher average pressure, tend to have marginally lower peak pressures, as less ignition advance is required.
Moving on to the combustion chamber itself we need to consider minimizing crevices and sharp corners within the combustion chamber and maximizing the quench/squish potential. With most wedge chamber motors as well as 4 valve motors with limited squish/quench area optimizing the piston to head clearance at TDC can prove very rewarding. Within the limits of what is typically seen on production motors we find that there is about 1% gain in output for every 6 thousandths of an inch (0.15 mm) reduction in piston to head face clearance made.

Swirl, Ignition and Timing.

High swirl and rapid mixture motion from a tight quench/squish clearance almost inevitably leads to a more effective and consistent combustion process. However it does not always lead to a more easily ignitable charge. Regardless of the effect of rapid mixture motion high compression ratios call for high performance ignition systems. When choosing an ignition system for a high compression motor it is far better to go into a gross overkill mode rather than spending time finding or simply accepting what is just adequate for the job in hand. This means utilizing an aggressive ignition system. By going this route the point of optimum advance can be reduced by 2 or 3 degrees. This in turn leads to lower peak pressures thus leaving room to possibly increase compression even further or have a wider detonation buffer zone.

Aggressive ignition and minimizing the optimal advance is not the only issues here. Because the cylinders of a multi cylinder motor will almost certainly run at different temperature there is a real need to be able to time each cylinder independently. In addition to this there can be differences in the volumetric efficiency and fuel distribution with motors having one carb feeding a number of cylinders such as is the case for a single 4-barrel carb on a V8. All this leads to the need for independent timing of each cylinder so that the worst cylinder does not compromise the best. Some test data we were privy to showed, on a Winston Cup motor of nominally 730 hp, that individual cylinder timing was worth about 12 hp.

Optimizing Chamber Form.



The last points that we will discuss here concerning combustion chambers relates to the chambers compactness. The fact that ultra high CR's are being sought means the object of the exercise is maximum power. This also infers the need to turn maximum rpm. If so short stroke/big bore motors look like the way to go because they can also accommodate bigger valves and turn more rpm. Unfortunately going this route tends to generate thin section, large diameter combustion chambers having a high surface area to volume ratio. This brings about a higher heat loss and the thinner sections of such a chamber (in and around 120 thousandths of an inch) tend to be prime candidates for detonation. Additionally the flame travel path on such a motor is longer. None of these situations are desirable and represent something of a critical balancing act when building a ProStock motor.

If very high compression is required of a big bore/short stroke unit the piston crown form inevitably becomes critical. Many years ago a motor project I helped Tucson head porter Carl Schatilly work on serves to demonstrate the difficulty high dome pistons can present. Basically the test motor was a wet sump, low cost Winston cup motor replica. With high dome pistons delivering 13.5/1 compression the motor marginally failed to make 400 hp. The heads were removed and the flame pattern inspected. It was obvious (as expected) that all was not well here. The simple expediency of a file was used on each piston crown to remove metal so as to get areas that were burning to communicate with those were it was not. By the time the crowns were modified to the extent of reducing compression to about 12/1 the power was up to almost 550 hp. The point demonstrated here is that effective combustion cannot be traded for compression.

The Mechanics of Effective Combustion Vs Compression.

All the forgoing demonstrates that attempts to harness the benefits of high and ultra high compression can easily lead to the combustion process being compromised. The thinner the combustion chamber cross section becomes the harder it is to burn the charge effectively. Because of better proportioning this means that long stroke motors are better candidates for high compression than short stroke units. Unfortunately a long stroke has a smaller bore diameter which limits valve diameter to something less than it's big bore/short stroke counterpart. The smaller valves mean less breathing potential. This leaves us with a cylinder that, though more suited to high compression, needs that same high compression to compensate for a loss in breathing capability.

The need for high compression and high rpm is the principle driving force behind the trend over the past 15 years toward shallower valve angles for high performance 2 valve heads. The original 23 degrees used for the small block Chevy was fine for 1955 when CR's were not expected to exceed about 10/1 or so. Putting a 14/1 ratio into a 350 cubic inch motor almost inevitably leads to an ugly piston crown. By adopting 18 degrees to bring the valves to a more vertical position a more compact combustion chamber form could be achieved.

If, for a given cylinder head the stroke can be lengthened such as is so commonly done when building a 383 out of a 350 SB Chevy then, for any given ratio, an improved chamber form will be achieved. This is brought about by virtue of a flatter piston crown for any given CR.

Conclusions.

If all the details suggested here are taken into account compression ratios as much as 1.5 higher can be accommodated from fuels in the 90-100 octane range. For a MotorTec built aluminum headed 350 small block Chevy with computer managed ignition curves, this has led to the use of CR's as high as 11./1 on 93 octane (R+M/2) fuel. However our efforts and results may yet still be conservative as to what can be achieved. Although shrouded in typical race engine builder secrecy rumors have been heard of motors with as much as 12.5/1 running successfully on 93 (R+M/2) octane fuel. The technology is here and it just seems a case of chasing it.