Sparkplug reading observations by Bruce Robertson. www.smartcarby.com

This is about performance tuning not tuning for emissions or maximum economy, strictly racing here. This is about tuning on the rich side of stoichiometric. It is impossible to separate sparkplug deposits from the subject of vaporization.
However I will restrict the references to vaporization to a minimum.

Overview.

Much is written about reading sparkplugs. The view that it is an exact thing to do is presented often, however I have found it's far from that. What deposits there are on a plug can't be related to a simple cause remedy chart. About all you can be certain of is if the plug is covered in oil, then you have a problem. The environment in the cylinder is a combination of anything that will burn and oxidize and the sparkplug is only a window to the zone immediately around it. It doesn't really tell you what is happening far away from it.
Reading a sparkplug is like reading the rest of an engine's signs, you have to be flexible in how you apply opinion. What I mean by this is it's better to observe the deposits and think about how they could occur rather than always deciding the same answer based upon a cursory examination. People ask me to read their plugs at race tracks and I have to ask them a lot of questions to do a proper job. You need to know what ignition system is used and what compression and power output etc. The questions vary for each sparkplug I have ever looked at.
The sparkplug has 2 main functions (apart from plugging the hole).
Firstly it has to obtain sufficient heat so that it doesn't get coated with electrically conducting carbon.
Secondly it has to place the arc in an effective position within the chamber.
The heat range of the plug is one of the factors that affect the way the engine runs. When the heat range is correct the engine will make more power and need less ignition advance. What you have to manage by heat range is the temperature of the mixture surrounding the porcelain. That is the area of greatest effect. There are other things like selecting heat range so that the plug doesn't get too hot etc but I'm not talking about those obvious things. You can look up charts from NGK etc about those factors.

Let me start by describing different areas.
1- The exposed surfaces of the center electrode
2- The strap or ground electrode
3- The outer surface of the porcelain near the roll at the top of the porcelain and the flat section going across to the center electrode.
4- The sides of the porcelain down to about 3/16th of an inch above the base of the porcelain
5- The base of the porcelain where it meets the metal area of the body including about 3/16th" above that.
6- The inner surface of the body of the plug that is exposed to the combustion gases.
7- The threaded area.

This is what each area is used for with plug observations

1- The exposed surfaces of the center electrode.

Specifically the flat surfaces where arc discharge occurs.
This is where you can see the amount of electrical energy available from the ignition system to ignite the available combustible mixture. The shape of the arc discharge, the area used by the arc discharge, the way the electricity busts up the molecules is all evident here. The electrons clean the area that is the exit and entry points. When you look at the end of the center electrode make note if the whole of the surface is clean. If it's only clean in one spot then the arc is occurring in that area only. This causes a problem, the surface of the metal heats up where the electricity flows and heat increases resistance to electricity so unless the electricity is discharging from the entire area of the surface the heat build up will be greater if there is only a small discharge point. The reason why the discharge is restricted to a small area is usually incorrect alignment of the strap electrode to the surface of the center electrode. The two surfaces need to be parallel. The electricity takes the path of least resistance, the resistance is determined by the heat and distance apart of the surfaces and the conductivity of the mixture between the gap. If the surfaces are not parallel the path of least resistance is the closest point, however as the run time increases the temperature rises at that local point because of continual use, so then the arc will move to another position that has the least resistance. The disadvantage of non parallel surfaces is that after some run time the electron path is not occurring in the least resistance that would be possible if the surfaces were parallel. It always will be occurring in a less than optimal position for what could be possible with correct gaping.
Any increase in resistance across the gap decreases the current flow. As the voltage required goes up, the amperage available goes down. The coil only has a fixed energy level and the need to increase voltage reduces the current flow across the gap so that the energy delivery is the same.
There are many people who advocate from theory that high voltage is the prime consideration in spark arc, they often teach that high voltage and long durations are necessary but my practical experience is that on high compression well vaporized mixtures with racing fuels, its more beneficial to have a given energy delivered in a short sharp shock. CDI is just such an ignition system. Inductive has never beaten a CDI in any of my tests. The MSD 10+ ignition is a combination of both designs and is excellent but an overkill for some street uses. The Crane HI-6 system has proven adequate for just about any application without causing the condition of arc punch through on some engines. Arc punch through is when the electricity is so powerful it prohibits mixture from interacting with the electron flow. If an engine is low compression it doesn't need a MSD 10+, using an ignition that powerful on a low compressing engine will result in arc punch through.
If the ignition system is low in energy output less of the surface is used and you will see deposits on the surface of the center electrode where the electricity is not discharging from.
The reason a powerful ignition system can sometimes not clean the whole surface is resistance or leakage from the plug wires or cap etc. It is essential to check the electrical integrity of the ignition system. The more powerful the ignition is, the more

likely there may be leakage. All ignitions systems should be tested with an oscilloscope. Scope data of high sampling rate and accuracy with data logging straight into a laptop etc like a Pico scope is essential to understanding combustion with engines developing high cylinder pressures.

Heat range.

The heat range of the plug is primarily controlling the heat removal from the center electrode of the sparkplug. If the electrode is too cold, deposits can form on the side of the exposed section of the center electrode. All deposits that I am aware of conduct electricity. Deposits on the side of the electrode cause increased leakage of the electricity via other deposits on the porcelain. Anything that leaks the energy from the arc can cause inefficient combustion.

This bring into question the effectiveness of the sparkplugs sold with multiple strap electrodes and a very short center electrode. Some designs have the center electrode virtually flush with the top surface of the porcelain. The arc has to travel along the surface of the porcelain for some distance or it has to travel very close to it. So its likely to leak on any deposits on the porcelain. In a direct test done those types of plugs tanned on a 14.7 consistent EFI engine (indicating ineffective carbon combustion) and the standard type of plug didn’t. The emissions were improved by the standard type plug indicating inefficient combustion overall by the so called improved design. To date I have yet to see a sparkplug design that is an improvement over the age old design. On all tests people have done to prove their new design work better I have found combustion problems caused by other factors that once corrected the age old design then proves to be best. There is more to plug design that simply arc and resistance etc. For instance, having 3 ground electrodes inside the flame kernel removes heat from the flame kernel resulting in less effective flame kernel formation.

When observing deposits on the sides of the center electrode.

The deposits here should only be light after a lot of miles on the engine. If the deposits are building up with a few runs the plug is too cold. Deposits of any type here can cause electrical conduction and wastage of some or all of the spark energy.

2- The strap or ground electrode

The projection of this into the cylinder is the most important factor to the combustion. When the arc is too close to the head surface the arc occurs in the boundary layer gas. When the arc is in the boundary layer it is not in fresh air. The boundary layer is not effectively scavenged. Different combustion chamber design and valve seat angles and different porting alters the scavenging of the boundary layer. The boundary layer is possible to be.040" thick but that is unlikely in that part of the engine. But I have gained 800rpm's of torque converter stall in some tune situations by projecting the plug further into the chamber. The optimum arc location depends on the amount of vaporization that occurs around the arc location. If the mixture distribution is improved then the arc can be further out in the cylinder. The further out it can be used the more power the engine makes because the flame kernel is able to grow in a more spherical fashion and more molecules are engaged in early combustion. That greatly increases the energy within the cylinder. When tuning to test projected arc locations it is important to reduce the ignition timing first. And one must proceed carefully.

3- The outer surface of the porcelain near the roll at the top of the porcelain and the flat section going across to the center electrode.

This area shows the coloration of the very first part of the flame kernel. It is a zone that gives clues to the changing burn of the flame kernel during the time of electricity duration.

4- The sides of the porcelain down to about 3/16th of an inch above the base of the porcelain.

This is read in conjunction with the reading of #3. Changes in color between #3 and #4 can be used as a gradient indicator of the burn style.

5- The base of the porcelain where it meets the metal area of the body including about 3/16th" above that.

This never gets hot enough to alter or remove deposits. Dark grey is rich side of stoichiometric and is the common colour aimed for with Holley style carburetion. However tan is possible and usually occurs on high power per cubic inch cylinders. Deposits formed here are due mainly to the lower heat input to the mixture, which is because the base of the plug is cooled by the water jacket. The gas level present here is greatly affected by the scavenging process. If the scavenge is inadequate to clear gases from the base of the plug a few possible conditions can arise. The gas composition present here after scavenge is important too. If the gas is predominantly CO_2 the resident gases could add heat to the incoming charge and assist vaporization without adding a fuel gas to the mixture. If the gas is CO the mixture will be heated less but a fuel gas will be present. CO has a very low heat output and it tends to create a grey deposit. If the zone is effectively scavenged the heat must be sufficient to vaporize the fuel to a sufficient gas state, if that’s not achieved yellows or greens appear near the base. If sufficient vaporization is achieved then light deposits of tan etc will appear.

6- The inner surface of the body of the plug that is exposed to the combustion gases.

This indicates the effective cooling of the body by the water. The type of carbon deposited here can vary a lot because of what style of burn is happening. Here you can see the effect of water temperature on the vaporization, It is through experience at looking at lots of engines and understanding their intricacies in various weather conditions that you learn how water temperature affects combinations.

7- **The threaded area.**

The threads should never be exposed in the chamber. It is necessary to check the thread length of the plug and to determine if any thread is exposed inside the chamber. This must be done with the cylinder head removed from the engine. If any thread is exposed to the chamber the temperature of the strap electrode will be raised significantly. The strap electrode looses heat to the cylinder head via the transmission path of the threads.

The threads that are engaged within the head can still get dark deposits on them. What they indicate is the cylinder pressure. If the threads don't show any signs at all of dark creeping up the threads then the engine is a slug. A good engine will blow deposit colouration up to 2 or even 3 threads.

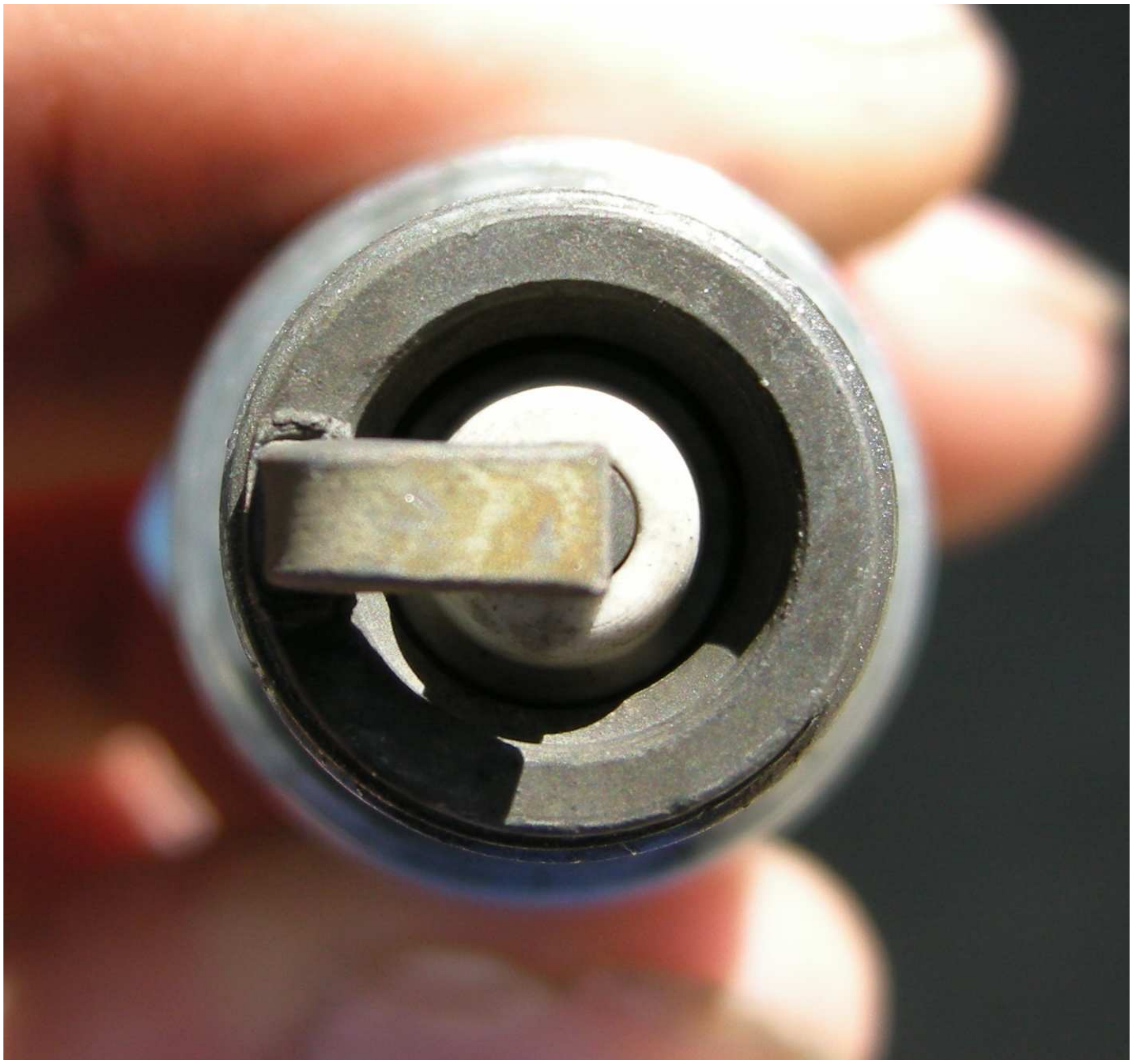
What is plug colouration?

I have asked that question for many years and never had a satisfactory answer. It could be said it's an amorphous solid but that's a fairly general term. I have been unable to actually define what elements cause colouration but there is a link to the emitted gases of the engine and the sparkplug deposits. So I did my own testing of it. When running an engine lean of stoichiometric, green deposits occur on the strap electrode or on the porcelain. All fuels will do it, alcohols or petrol's. When the vaporization of the fuel is made to be less, a more intense green or yellow deposit appears on the strap or porcelain and the gas readings show high levels of oxides of Nitrogen. Green is leaner than Yellow. Yellow is not really a problem unless the engine is a very powerful one but green needs to be avoided in racing engines. So I propose that Nitrogen and its associated compounds have a role in the formation of green and yellow deposits. Nitrogen when compounded with Carbon and Hydrogen makes many powders that are white or off white colour It is proposed by others that yellow is lead fouling but unleaded fuel can display yellow so that is not consistent to that claim. The intensity of the green is related to the usable AFR surrounding the plug at ignition time.

When the engine is run rich and well vaporised the deposits are a tan to red colour and the gas readings are virtually no NOx and some unused HC's. It's probable that Carbon with dispersed Hydrogen forms reds and browns.

I have seen (but have no photos of) plugs where the strap is green and the porcelain is tan. My deduction of that situation is that the vaporization is low but it's a rich mixture, so doing work that improves the vaporization has resulted in full tan on those engines with no green. The gas bench reading has supported this by showing high HC levels with NOx. I have even had the opportunity to test clear petroleum, no added dies, and it colours the same deposits for the same reasons. Methanol colours the same in the same conditions and unleaded petrol is no different to leaded.

Here are some photos of plugs and discussion about them.

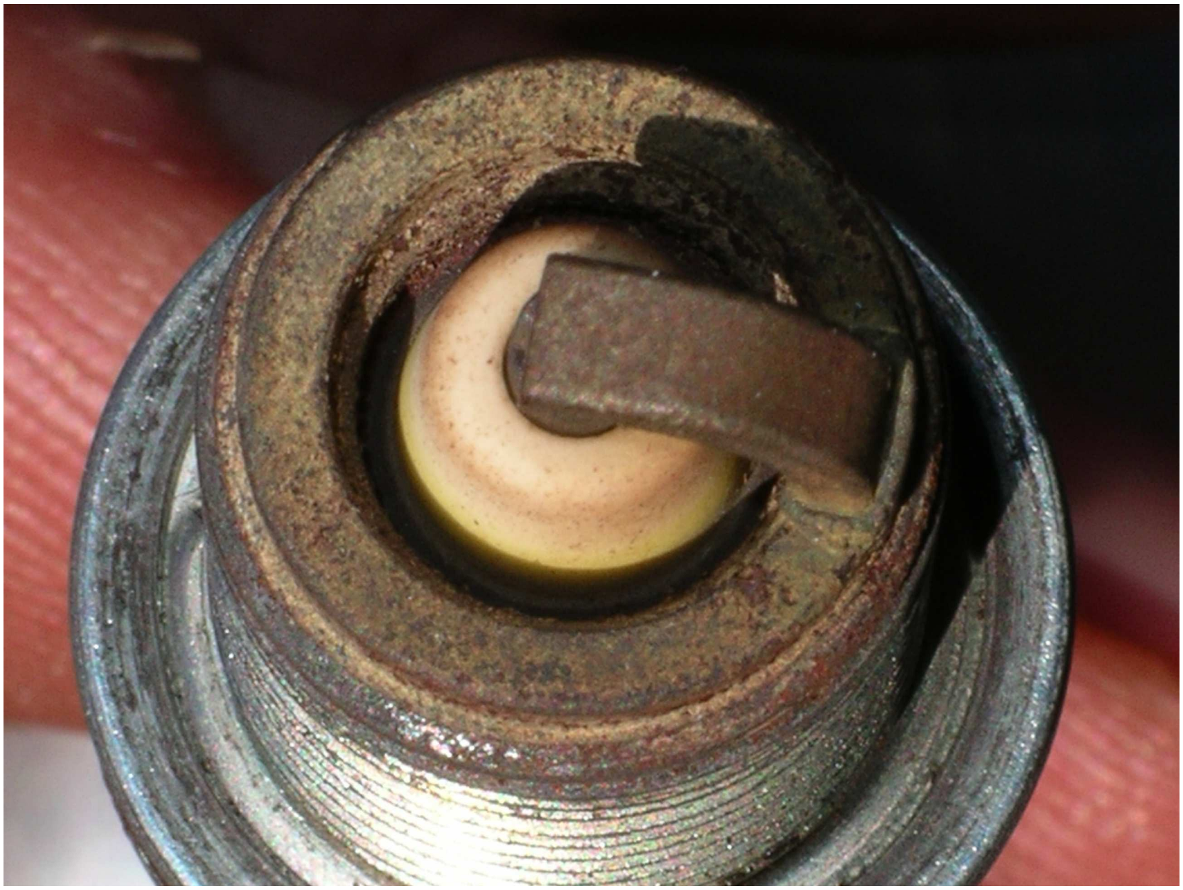


This plug is very interesting. The stripe effect on the strap electrode shows the various colours that normally get deposited. There are areas of no deposit, areas of white and areas of brown. It is interesting how the deposits are forming in stripes. The engine that formed this plug is an alcohol - supercharged Keith Black 526. It was burning lean. So lean that if they richened it up at all it melted the sparkplugs. The striped zones of different colouration are possibly happening from a flame kernel that is erratic in its growth rate. This is what I would expect to happen if the mixture is too lean. There is not enough heat to maintain consistent flame growth. The fireball is depositing the brown areas where the HC concentration is highest then it is depositing the white in the areas that are leaner.

This photo identifies electrode wear on the strap end. This is the same KB engine. All the plugs wore this way. The arc discharge is evident only at the zone where the wear is happening. What is happening in this engine is the arc is weak. Its fitted with a Mallory 4 amp magneto. That is way too small to give good ignition to a methanol engine on 25 lbs boost. Methanol is highly conductive to electricity. This causes a situation where the arc energy has to have enough rise rates to blast the methanol even if it’s a liquid in the path of the arc. Once the arc has started to discharge, liquids will be vaporized but they still have to be heated to ignition temperature. That takes time, and by the time that has started to happen the arc has sufficiently ionized the environment and the ionized molecules are being blown out of the gap area towards the end of the strap electrode. This is a common direction for arc to be blown. The most effective part of the arc at ignition of the mixture in this example is the end of the strap that is being eroded. Erosion of the metal is actually like a flint gun. Metal particles are being sprayed across the gap. Erosion of the electrodes is not detrimental to the performance provided the plugs are changed before it gets too bad; this example is too much erosion for this engines ignition system. The engine was originally set at .026” gap and I recommended .016” to .018”. This lower gap allows the ignition to pass amperage through the gap quicker and ignites the mixture with a sharper definite kick. Low amperage magneto’s work best with small gaps. Generally a 6 amp magneto can run a .028’ or slightly larger gap. A 12 amp magneto can run .036” or larger.

This plug is from an engine that has not enough compression of the chamber for the type of fuel. There is a lot of evidence of lead compound contamination. Lead compound contamination occurs when the temperature range of the area is below the temperature needed to activate the scavenging chemicals in the fuel. This engine is running VP 110 fuel and generates approximately 535 hp from 406 cubic inches. It looks like it's been in the engine for a long time but that is not the case. This engine quickly generates plugs like this. Note the erosion of the center electrode. This erosion will occur to this level in one run down a drag strip with this engine. The reason for the extreme erosion in this case is the lack of vaporization of the mixture at ignition time. If the mixture within the gap is under vaporized the mixture will ignite lean. The excess oxygen within the gap corrodes the metals there very fast.

The mixture of this engine is rich at lambda 0.85. The strap electrode is showing high levels of brown deposit. But there is not a matching level of brown on the porcelain. This is indication of differences in vaporization in the flame kernel area compared to within the chamber mixture. The chamber is always going to vaporize the mixture more than the flame kernel because the chamber has had more time and heat to achieve a higher vaporization level. The ignition system in this engine is a MSD digital 7.

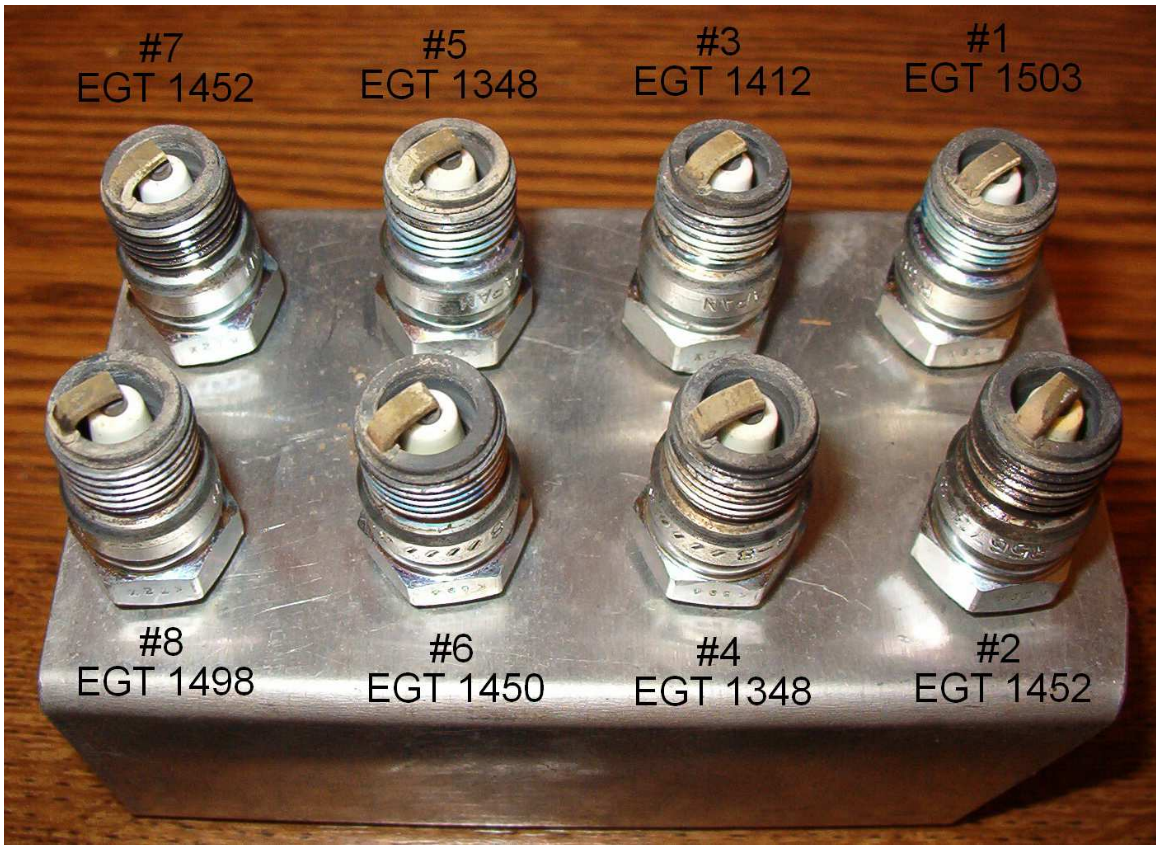


This plug is from an engine using 2* 1085 cfm 6 barrel SmartCarby carburetors. The compression ratio of this engine is 15.3 to 1 and the cranking pressure is 300 psi. Fuel is VP C14+ (a leaded fuel). The engine timing is 28 degrees. This is lambda 0.83. Note how the shell has Hydrocarbon deposits on it that are consistent with the strap electrode and the colouration on the porcelain. This is indicating a good consistency of overall mixture with possibly optimum ignition timing. It is a well vaporized rich mixture. There is no evidence of overheating..

This plug is close to ideal but it's not right in some ways. This from the same engine as above but at lambda .87. But there is very little colour on the porcelain. This engine is using SmartCarby carburetion. 2 * 6 barrel 1085 CFM carburetors. You will notice the difference in deposit granule size by improved atomization. This is one drag strip run. After 4 runs the porcelain also slightly colored with tan, with the shell remaining clean. The cleanliness of the outer shell indicates close to complete hydrocarbon burn but the strap electrode indicates an excess hydrocarbon burn, (oxygen deficient). Clearly there is a difference in the mixture close to the head compared to further out in the chamber.

There is no evidence of overheating. The line on the strap electrode that is near the weld is sometimes interpreted by tuners to be evidence of the ideal ignition timing. The rule is often quoted as being to adjust the timing so that the line appears in the middle of the bend of the strap electrode. I do not agree with this theory. There is ample evidence from improved atomization style burns that this line exists only under some conditions and I have not been able to establish a link to the optimum timing degree. It is not as simple as that.

This plug is the same engine again but running 2*780cfm four barrel carburetors by SmartCarby. This is Lambda 0.87. This is one drag strip run. There is no grey at the base, indicating no CO. A good quality burn with low engine wearing characteristics. The outer shell has consistent deposits throughout, water temperature is not an issue, the strap is nicely coloured with very even fine deposits. It’s possibly a smidge lean, it might have been the air density of the day etc. It’s nice to work with an engine like this. The lower CFM carburetors have altered the atomization of the fuel and the result is better temperature control even when slightly lean for the load and a more readable deposit within a short time giving readable results. The combustion temperature is probably high as indicated by the appearance of slight yellowing on the lower band and yet the strap is not stressed. I cannot provide information of the total fuel flow as there is no data logging of that on this car but it used significantly less fuel to achieve the same lambda as the first photo from this engine shown above.



The plugs above show the irrelevance of correlating EGT to plug colouration.

There is no correlation between exhaust temp and burn sparkplug colouration. The ex temp is a measure of the wasted energy from the gases that managed to burn. The colour is the amount of carbon that burnt. That’s why the caption reads what it does. These plugs are from a BBC that has a 1050 dominator on it and makes 530hp. It’s a drag car. What this is an example of, is showing you that you can have different colours with the same amount of wasted energy. For instance 2, 6 and 7 are the same temperature and yet number 2 has colour. The brown plug and the clean plugs are the same temperature but you ask how come? Well the energy output of the brown and clear plugs cylinders is the same percentage of the fuel consumed. That’s why you have to correlate information form different factors to correctly read an engine.

You can have the same power percentages of the fuel load of the cylinder with different fuel loads. Different fuel load make different power because of the relationships of CO and low temp verses CO2 and high temp. The brown plug cylinder has high CO and low temp slow burn. The cleaner plugs have lower CO and more CO2 and higher temp faster burns. The exhaust temp is a measure of the unused energy from the fuel that has been burnt so the mechanical conversion of energy lowers the exhaust temp. If the temps are the same but the plugs look different then the power output from the cylinders will be different and that's exactly how that engine in the photo runs. It has jumpy AFR and rough running of the rpm trace. It's a fairly common Holley engine.

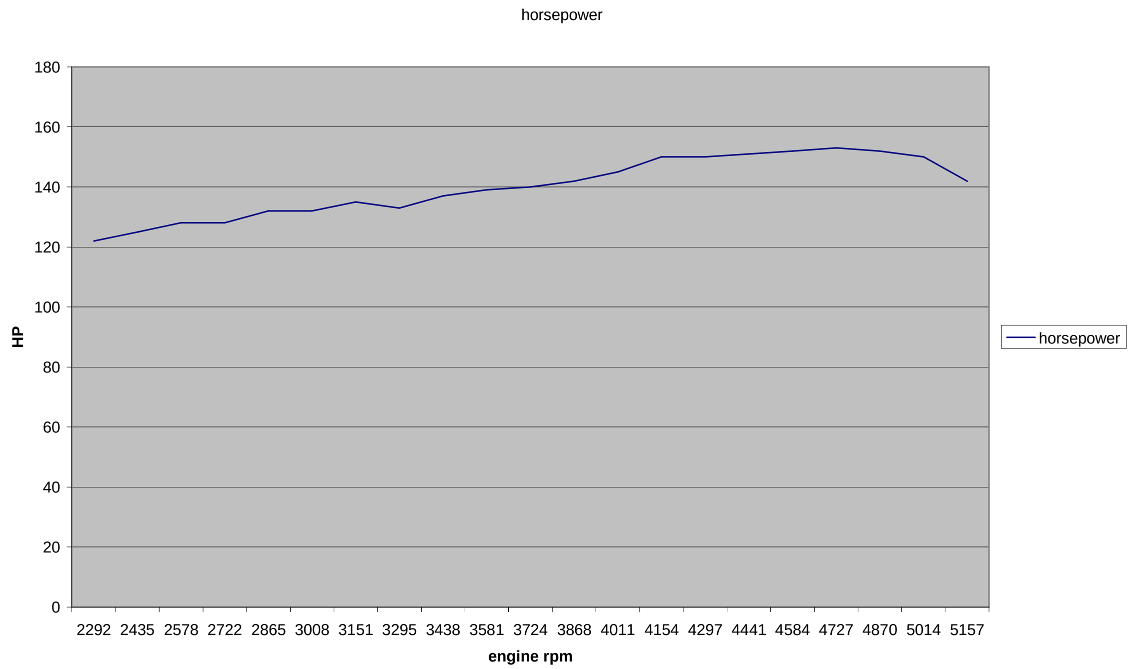
This plug is exhibiting arc blow. What is happening is the arc is being blown away from the electrode gap by extreme turbulence. You can see the arc blackness on the porcelain. The photos below is that plug from the other side. The index of the plug is such that the side showing in the photo below is facing the intake valve.

Here is another arc blow plug

It is easy to see the damage to the center electrode and that the arc is blowing out to the outer shell of the plug. The intake valve is toward the back side of the photo. You need a powerful ignition to achieve this level of arc discharge and not get a misfire. This is a MSD 10 plus ignition. The engine did not misfire when arc blow out occurred but it changed exhaust sound and lost some power.

This plug is from a 308 Holden running unleaded street fuel. The engine made 153hp at the wheels. It had every ring broken on every piston; it had leaking valves and a smoke trail 3 feet long pouring out the breather but no smoke out the exhaust. You can see the tan colouration forming at the base of the porcelain and some tan specks starting near the 4 o-clock position near the roll on the top of the porcelain (its in the shadow a bit). But you can see tan easily on the strap electrode. The outer ring deposits are not soot and there is no evidence of oil combustion. The outer ring colors appear to be rainbow like but that's a digital camera anomaly, it wasn't like that to the eye. This picture shows what good vaporization can achieve on a stuffed engine. When using large droplets this engine produced oiled and soot covered plugs and blue exhaust smoke. So I retuned it for smaller droplets and it responded well.

This is a plug from the same stuffed 308 but it’s a high mileage general use photo. You can see the formation of tan graduating to dark grey at the base of the porcelain. This is unleaded street fuel. The mixture is leaner at the outer ring due to cruising AFR’s etc.



This graph is the HP output from that 308. It’s measured at the wheels. No correction factor. Interesting Hp line huh!

This plug is from a race engine running C14+, 15.5 compression ratio achieving 240psi cranking pressure. 1050 Holley Dominator. The Lambda of this burn is 0.78, that's quite rich and yet there is hardly any carbon deposit. Note the carbon built up on the inside of the shell, but its not on the porcelain or strap etc. These racers try to run their engine with cold water temperature. The carbon is building on the water cooled areas. The black spots on the porcelain are not detonation dots they are small flecks of loose carbon blowing off the shell etc, you can see that clearly with eye piece magnification. Note the surface appearance of the porcelain around the exit point of the center electrode; it is nice and smooth with no roughness.

See the little black arrow on the picture that's pointing to a brown spot, you cant see it on the camera resolution but in the center of the brown dot is a small area of cleaned metal that has been blasted away by detonation. Now bear in mind that this is very rich and the timing is 34 degrees. The timing was advanced further earlier in the day and it made more power but it was more serious detonation. After this test I richened it two jet sizes and the picture below is the result.

The same plug after one dyno pull of richer mixture. It made more power. The tan spot has cleared up, there was no evidence of blasted metal but the porcelain has started to break down in the joint to the center electrode. You can see the depth of the carbon deposit on the shell easily in this photo. No matter how much fuel you chucked at this engine the plugs always read like this, even when it was over fueled that much that it lost 40kw. It lost power running leaner, it has combustion problems. It continuously made extremely high CO and low CO_2 and had 4% oxygen left over. When I did the gas balance calculation on it there was the correct fuel for Lambda 0.87 and the Oxygen left over was exactly sufficient to complete a Lambda 0.87 burn. Observing the lack of carbon on the plug informs you that the environment at ignition time is lean and therefore the vaporization is low. The flame kernel is therefore slow growing, hence the increase in power with more timing, but the fuel octane wasn't enough to prevent detonation under those pressure conditions at that lean ratio in the vicinity of the plug. The strap electrode doesn't exhibit heat or anything else detrimental and C14+ is 115 octane fuel so what are you going to do to fix the issues? The real problem with this engine is the lack of energy input to the fuel up until ignition point, if there was more energy input there would be more vaporization and a richer environment and it wouldn't detonate and the plug would get carbon on it.