ATTACHMENT II

THE "SPLIT FIRE" SPARK PLUG: THEORY OF OPERATION AND MARKETABILITY

BY PAUL V. SHERIDAN

ENGINE PROGRAMS MANAGER

CHRYSLER MOTORS CORPORATION

INTRODUCTION

Twenty years ago the American automotive marketplace was on the verge of its most fundamental change since its practical inception by Henry Ford's Model T in 1908.

Prior to the imposition of strict government regulations for fuel economy and exhaust emissions, automobiles were judged on the basis of criteria that appeared to be at odds with the coming standards. Power and performance seemed to be the technological opposites of legislation such as Corporate Average Fuel Economy (CAFE), the "Gas Guzzler" tax or reduced levels of tailpipe pollutants. It was in this respect that major technological changes to automotive engine systems were seen as required to simultaneously satisfy the new regulations and hopefully the consumer's ongoing preference for performance. Indeed, the vision of a full-size luxury automobile, such as the Chrysler New Yorker, being able to accelerate faster than the cars of the "good ol' days," getting nearly 30 miles per gallon on a highway cruise, and doing so with exhaust emissions at one-hundredth (!) of the 1969 level appeared to be a distant, expensive dream. In fact, many considered this virtually impossible.

AUTOMOBILE ENGINES: THEN AND NOW

Looking under the hood of a twenty year old automobile, and comparing it to what you see today is frequently described as "mind-boggling." Surprisingly, the engine compartment represents only a portion of the massive changes that have taken place.

In addition to the well-known engine downsizing, the use of electronic fuel injection, "fast-burn" cylinder heads, tuned intake and exhaust systems, advanced lightweight materials, and high energy distributorless ignition systems are just some of the changes that have been implemented. Catalytic converters, electronically controlled overdrive transmissions, sensor systems and computer-based powertrain management systems also comprise the major technological changes.

It must be emphasized however that major changes to discrete powertrain components are just the tip of the proverbial iceberg. Although not as apparent, the process by which the components themselves are manufactured have undergone even more dramatic changes. Advanced manufacturing methods such as statistical process control (SPC), Quality Improvement Processes, (QIP), artificial intelligence (AI) computer integrated manufacturing (CIM) and the highly publicized use of robotics have all made major contributions to today's automotive engine systems. For example, what would have been an acceptable level of cylinder roundness (cylindricity) and therefore piston ring seal on yesterday's engine, would be considered a "disaster" by today's standards. In fact, current cylinder boring and honing operations are completely robotic, utilizing artificial vision and laser-based quality inspection systems that rival, perhaps surpass, the technology and acceptance standards employed in the construction of the Space Shuttle!

In the context of the ever tightening fuel economy and exhaust emission regulations, yesterday's automobile engine is simply not a device worthy of comparison. For example, in today's engine the operating variables of air-fuel ratio, exhaust gas oxygen, engine coolant temperature, exhaust gas recirculation, manifold-absolute pressure, mass air flow, to name a few, are not only monitored but many are automatically adjusted at the staggering rate of thousands of times per second.

By comparison, yesterday's engine was operated with these variables statically adjusted and "monitored" only at the time of a periodic tune-up. These engines would seemingly perform satisfactorily with many of the adjustments "way off." The word "seemingly" is emphasized since, in the context of government regulations, these engines were rather sloppy. In fact, previous engine designs failed to respond to somewhat minor changes because most of the design, component and manufacturing tolerances were too loosely defined or controlled.

Similar to many racing engines, current production engines are exactly the opposite. With the major technological changes already implemented, minor changes to the status of an operating variable, a manufacturing tolerance or the design of a component will have very noticeable effects. It is from this perspective that a theory of operation for the "Split Fire" spark plug can be formulated.

SPECIFIC OUTPUT, HEAT AND SPARK PLUG DURABILITY

One of Detroit's initial responses to the fuel economy and emissions regulations was the downsizing of not only the overall vehicle but the engine system as well. In order to maintain equivalent power and performance to their predecessors, current engines are required to produce far higher levels of what engineers call specific output. This term merely describes what a discrete amount of engine displacement produces at peak horsepower or torque. Today, specific output is given as horsepower per liter (Hp/L) or torque per liter (Tq/L). For example, the current 3.0L V-6 engine used in the Chrysler New Yorker produces 141 horsepower and 171 foot pounds of torque. Dividing these two numbers by 3.0 liters yields specific outputs of 47.0 horsepower per liter, and 57.0 foot pounds of torque per liter.

The purpose of these calculations is to place engines of similar design configuration on an equal footing, and therefore provide a more direct comparison of their actual engineering content. For example, a pre-regulatory engine may have produced a true 250 horsepower, but requiring 7.5 liters to do so would yield a specific output of only 33.3 Hp/L. This figure represents a deficit of nearly 30% versus today's New Yorker engine. More importantly, it clearly demonstrates the impact that the technological changes have had on true engine output.

Impressive as these figures are, there is a price. In the process of producing high specific output, current production engines also necessarily create more heat in their combustion chambers. Indeed, an engine's ability to more properly process heat energy into usable work at the crankshaft is exactly why its specific output increases. Unfortunately, increased heat creation has a drastically negative effect on combustion chamber component durability. In a vast majority of mechanical systems, higher component temperatures tends to imply higher wear rates. To alleviate this engineering compromise, Detroit has had to resort to extensive and expensive material upgrades to the pistons, piston rings, the cylinder head gasket and, the intake and exhaust valves. **Surprisingly one of the most important constituents of the combustion chamber has not substantially changed in nearly 30 years...the spark plug!**

To understand why is merely a matter of financial analysis. If one of the other combustion chamber components fails, major overall and expense are the outcome. On the other hand, spark plugs were originally designed and continue to be low cost maintenance items. If the spark plugs wear out or fail, the cost is minimum in both time and expense. However, there are several very important reasons why this scenario is no longer tenable.

The **first** involves contemporary consumer expectations. The automobile buying public has become less tolerant of the high frequency maintenance requirements previously suggested by the manufacturers. To an ever increasing extent, the consumer wants to "turn the key and aim." Indeed, that's all they should be required to do given the high purchase price of today's automotive products. The exclamation, "They can put a man on the moon...why can't they make a spark plug that lasts?" is a common characterization of their attitude.

A **second** reason also directly involves the consumer. Today's regulatory environment at the manufacturer's level has also "trickled down" to encumber the owners themselves via the Auto Emissions Test (AET). Similar to the previous yearly inspection for basic safety items such as brakes, headlights, tire wear, etc., the owner is now required to submit their automobile to a "tailpipe inspection." Although the AET is admittedly less stringent than that required of the manufacturer, it does provide an indication of the overall condition of emissions control componentry. A key component is the spark plug, and therefore the consumer can increasingly be expected to demand a design that provides durable, trouble-free operation. More importantly, the spark plug must ensure expedient compliance with the yearly AET.

The **third** reason that spark plugs are no longer exempt from the rigors of overall durability involves proposed legislation from both the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB). At present the spark plug has an engineering classification of maintenance item. This status requires only a limited amount of life expectancy. However, both the EPA and CARB are proposing that the spark plug, among many other components, become classified as an emissions component. In the practical sense the spark plug will retain both classifications, but in the legal sense the latter category will require that the automobile manufacturers demonstrate certifiable durability for 50,000 miles!

No reasonably priced spark plug presently installed by Detroit's automakers have demonstrated an ability to comply with all three of these market forces, especially the third. Clearly a new approach to the spark plug is required for not only durability reasons, but for marketability reasons as well.

THE "SPLIT FIRE" SPARK PLUG: SIMPLE BUT EFFECTIVE

As mentioned, the spark plug is one of the combustion chamber components that has not undergone substantial change. Although many different configurations were proposed in the past, for the most part these attempts either lacked technical merit or were simply ahead of their time (see "Automobile Engines: Then and Now" above). The Split Fire is not only a design whose time has come, but it fulfills the requirements of numerous spark plug operating criteria. As the name implies, the Split Fire utilizes a negative electrode that is bifurcated to form a 30 degree vee that just clears the positive center electrode (as viewed from the combustion chamber end). Sometimes called the ground electrode or side wire, the negative electrode of the ordinary spark plug is constructed of a rectangular strap that completely covers the center electrode. This design is deficient versus the Split Fire in numerous respects.

THE COMBUSTION PROCESS, SMOLDER TIME AND SURFACE AREA

When the ignition and combustion process of automotive fuels is analyzed in the laboratory, one of the phenomenons that is typically observed is called slow fire or smolder time. Smolder time is a measurement of how long it takes from the moment the spark occurs until a full flame of burning fuel begins to propagate throughout the combustion chamber. There is nothing mysterious about this phenomenon. It is merely the automotive equivalent of throwing a lit match into a pile of campfire kindling, and waiting the usual delay until the fire "catches." The issue relative to automobile engines however, involves the smolder time effect on the side wire. By having a side wire design that completely covers the center electrode, the ordinary spark plug tends to momentarily trap the smoldering flame. Over long engine operating periods, the conventional side wire retains an undue amount of heat because it is essentially being "cooked" by this phenomenon. As implied during our discussion of spark plug durability, the combustion chamber components of today's high specific output engines must necessarily endure much greater operating temperatures. Between greater operating temperatures and an innate tendency to trap the smolder event, the conventional side wire has become the weak link in terms of spark plug life.

By contrast, the Split Fire design provides an open path from the ignition point to the main combustion chamber. The 30 degree vee does not block the flame from propagating and therefore minimizes the increased temperature effects on the side wire due to smolder time. Some will argue that side wire operating temperature problems can be solved by using alternative materials such as gold palladium or other precious metals. However the cost of this approach is prohibitive, in terms of materials cost as well as spark plug manufacturing process complexity. Whether in four stroke or two stroke applications, the Split Fire side wire design also offers greatly enhanced durability simply because of an increase in electrode surface area. By having the superficial equivalent of two side wires in proximity to the center electrode, the Split Fire provides twice the usual number of spark paths for the ignition system.

HEAT RANGES, FOULING AND PRE-IGNITION

Curiously enough, one of the most important parameters of spark plug design involves heat range. In fact, spark plugs can be configured to operate at higher temperatures by design! This is done by providing a longer insulator, and therefore a longer heat conduction path, from the center electrode to the spark plug housing. This greater distance forces the heat generated at the ignition point to take greater amounts of time to travel to the housing. The housing then acts as a "heat sink" to the cylinder head, dissipating the heat energy at a predetermined rate. The longer the insulator, the higher the spark plug operating temperature. The shorter the distance, the lower the temperature.

The primary reason for inducing a controlled operating temperature is to minimize fouling. Fouling is the condition where the electrodes of a spark plug are contaminated, and can no longer provide a reliable spark path for the ignition system. When the electrodes are fouled, the electrical resistance becomes too great for the ignition system to overcome, and the spark will not "jump" from the positive center electrode to the negative side wire. This causes the cylinder to misfire, wasting fuel and dramatically reducing overall engine performance. Typically it is oil, anti-freeze, carbon soot or fuel that causes fouling. Higher temperatures tend to "burn" these contaminates off the electrode surfaces, which tends to minimize fouling.

On the other hand, intentionally higher electrode operating temperatures will also jeopardize spark plug durability for the reasons discussed above. However, this is not the only concern when designing or selecting the heat range of a spark plug. For example, if the heat range is too cold, the plug will tend to foul. This is especially true in cold weather or idling conditions. If it is too hot, the plug will not only wear prematurely, but it will also cause pre-ignition. Pre-ignition is the engine operating state where the flame is ignited too early relative to piston location during its upward travel of the compression stroke. This is equivalent to incorrectly advancing the ignition timing adjustment beyond the recommended setting. Selecting a heat range that is too high causes the spark plug electrodes to operate at such high temperatures that they ignite the fuel before the spark arrives. Pre-ignition ruins the fuel economy, emissions, performance, and potentially an engine's mechanical parts. More importantly, it does so in a completely random, unpredictable manner.

Therefore, the technical compromise that must be managed involves selecting a heat range that "walks the tightrope" between too cold, which causes fouling, and too hot, which causes premature wear and pre-ignition. At present, the conventional spark plug suffices, but the Split Fire greatly reduces the magnitude of the compromise.

TURBULENCE

One of the most beneficial features of the Split Fire is its effect on overall combustion chamber turbulence. The Split Fire creates more turbulence versus a conventional spark plug because the split side wire design tends to "trifurcate" the flows into three distinct fronts. The conventional electrode design can only bifurcate the flows. In fact, the most important location for turbulence is between the electrodes of the spark plug. By inducing violent activity at this location, a drastic reduction in fouling is experienced. This is due to higher, more pervasive flow rates that, similar to high winds, tend to sweep the area clean of contaminants.

The subtlety is that, unlike conventional spark plugs, the Split Fire does not require the heat range necessary to maintain clean electrodes. The enhanced turbulence provides the needed cleansing action, thereby allowing operation at a lower heat range. This in turn avoids the problem of higher operating temperatures which tends to cause premature wear and pre-ignition. Indeed, this is the best of both worlds.

FLAME PROPAGATION AND INDEXING

In addition to greatly reducing the comprimise between heat range versus fouling and durability, turbulence also substantially improves flame propagation in the combustion chamber. For example, visualize a campfire that is burning without additional stimulation versus the campfire that is being aggitated by billows. The heat generated by the first campfire will boil water, but the campfire aggitated by the billows will smelt iron! This is caused by forcing fuel and air to unite at much higher rates, and therefore create far greater levels of heat energy.

This is basically what happens in the combustion chamber as a result of turbulence. The fire becomes more robust, more violent, and therefore more complete. A turbulent flame is more likely to propagate to regions of the combustion chamber where unburned fuel typically "hides". In engineering terminology, the turbulence induced by the Split Fire greatly enhances flame propagation.

Another benefit of the Split Fire design, as it relates to flame propagation, is indexing. This is the terminology used by racers to describe the painstaking task of orienting the spark plug electrodes to maximize the exposure of the spark to fresh fuel. Indexing simply rotates the side wire of the conventional spark plug away from the intake valve which then provides an unobstructed path for the incoming fuel to directly contact the gap between the electrodes. This helps to assure that when the spark arrives at the gap, plenty of fuel is present for ignition. In the situation where the side wire has its "back" to the incoming fuel, there is the finite probability that the spark will not contact any fuel, and therefore cannot initiate burning. The probability of this happening varies with combustion chamber design and engine speed. When it does occur, a misfire is the result.

Indexing the spark plugs is a very time consuming process that only the rigors of racing can tolerate. This is because there is no cost effective method of ensuring the correct side wire orientation in the context of mass production. There are simply too many manufacturing variables. On the other hand, the open Split Fire design tends to increase the probability of spark contact with the incoming fuel. Although not a true indexing, in the strict technical definition of that term, the Split Fire does reduce the geometric variables that cause periodic misfire. The impact of this feature is especially noticeable during idling or low engine speed conditions.

DELIVERED ENERGY AND CONTEMPORARY IGNITION SYSTEMS

The subjects of turbulence, flame propagation and indexing are all related to a recently developed concept called delivered energy. This term describes the ability of the combustion chamber, spark plug and ignition system to couple electrical energy to the chemical energy of the fuel. Referencing the "Indexing" discussion above, if the spark does not make contact with any fuel, the ignition process cannot take place. That is, a coupling did not take place and therefore no energy was delivered. The extent to which the available electrical energy is delivered to the fuel, is exactly the extent to which complete combustion can take place. Overall engine efficiency is greatly dependent on the level of delivered electrical energy.

One of the ways Detroit engineers have enhanced the amount of energy delivered to the fuel is to simply increase the energy produced by the ignition systems. These contemporary ignition systems are called High Energy Ignition or HEI. Although HEI does not approach the energy levels provided by racing systems, they do produce approximately double the energy of twenty year old designs. When the open path design and the enhanced turbulence of the Split Fire is combined with the HEI, the delivered energy is more than doubled versus previous configurations. In fact, vehicles that utilize HEI systems tend to benefit to a much greater extent than non-HEI, but both situations experience higher delivered energy and therefore more efficient operation.

CONCLUSION

The key points to remember with respect to the Split Fire spark plug is that today's high specific output engines, like racing engines, are far more sensitive to minor changes. Other than the introduction of copper core center electrodes, it is only the spark plug that has not undergone drastic design changes during the last twenty years. In fact, we can see from the simplicity and impact of the Split Fire design that a major change was not necessary. By merely reducing the magnitude to the compromises associated with the previous design, very noticeable and measurable improvements in engine performance, emissions, fuel economy and driveability can be gained. When these improvements are combined with the durability aspects of the Split Fire, it becomes highly probable that general availability will be demanded by the market.

FURTHER/ORDERING INFORMATION

For further information or SPLIT FIRE availability please contact:

Energy Performance, Inc.
P.O. Box 2372
Winter Haven, FL 33883-2372
813-324-4987
FAX 813-324-4895