Bell Performance, Inc. **tel** 407-831-5021
1340 Bennett Drive **fax** 407-331-1125
Longwood, FL 32750
www.bellperformance.net

BELL PERFORMANCE FUEL ISSUES SERIES
MOST COMMON DIESEL FUEL PROBLEMS

EXECUTIVE SUMMARY

Diesel fuel, the fuel of choice for most of this country's transportation and boating industries, is more prone than gasoline to problems with incomplete combustion, deposits and poor emissions. This is true on both the storage and user ends. Deposits on injectors, valves and in combustion chambers can all have negative effects on engine and equipment performance. Those who use stored diesel fuel are impacted by today's ultra-low sulfur diesel fuels having a shorter storage life, more microbial problems and a greater potential for cold weather gelling problems. Storage of diesel fuels lead to potential for oxidative breakdown, build up of harmful water in the storage tank, and microbial infestation of the fuel supply, which necessitates use of a biocide to eliminate the infection.

INTRODUCTION

Diesel fuel powers most of this country's over-the-road transportation, rail and large marine fleets (as well as many pleasure boats). In Europe, diesel cars are more common than here in the States. To be sure, diesel does offer advantages over gasoline as a vehicle fuel. Diesel engines tend to be more efficient, relying on compression ignition than spark ignition. They last longer as well, which is part of the reason they are universally preferred for large industrial applications.

Diesel fuel users may be aware of certain fuel problems that come with the territory. These problems can be classified as storage-related and performance-related. Issues such as fuel deposits in areas like injectors and combustion chambers, poor storage life, cold weather problems, and susceptibility to microbial growth in storage – they are all things to contend with.

DIESEL FUEL PROBLEMS IN STORAGE

The efforts to clean up diesel fuel to lessen its impact on the environment have given us fuel that is both markedly cleaner than ever before but also much more prone to costly problems, especially when it is stored in storage tanks. A large portion of the blame comes from the refinery processes used to remove most of the fuel sulfur. This ultra-low sulfur diesel (ULSD) fuel is the only kind of diesel fuel you would have been able to get since about 2010.

And it's got a host of problems that must be reckoned with – markedly shorter storage life than fuels from even 10-20 years ago, and a virtual absence of any ability to resist microbial activity in the fuel. This latter point is important, because it amplifies the traditional water problems that diesel has had in storage. In today's ULSD fuels, the water accumulation that is universal to storage tanks of all shapes and sizes now mean microbial growth and destruction of fuel quality to extents never really seen in years past.

Bell Performance, Inc. **tel** 407-831-5021
1340 Bennett Drive **fax** 407-331-1125
Longwood, FL 32750
www.bellperformance.net

DIESEL FUEL STABILITY ISSUES

Given enough time, any petroleum product – gasoline, diesel, fuel oil, natural gas – will react with things in the environment they are exposed to, like water, metals and light.

Light really just acts as a catalyst to accelerate oxidation chemical reactions – where oxygen reacts with the fuel molecules and causes them to react with other molecules – fuel or not - leading to the formation of polymers that react with other polymers in chain reactions. This is why diesel fuel poured into a glass jar and left exposed to sunlight will still darken over time – the oxidation reactions cause the color change.

Exposure to water or air can start or speed up fuel oxidation. Both water and air are excellent oxygen donators, and oxygen is the primary culprit in oxidation. Exposure to certain kind of metals (like copper) as the fuel passes through a fuel storage and delivery system – these can also start and speed up oxidation, although these kind of metals merely act like catalysts and oxygen would still need to come from another source (not usually an issue in the typical fuel storage system or tank).

Lastly, if the tank has a microbial contamination (more on that later), these acids given off by the microbial biological processes attack fuel and hasten its breakdown.

Over time, the fuel starts to separate and break apart, with these "heavy end" molecules agglomerating together and sinking to the bottom of the mixture (because they are the heavier molecules). Fuel which has oxidized and stratified like this loses its ability to combust at an optimal level. And this means the fuel isn't going to provide everything it's designed to, if it can even support engine operation at all.

This is an especially critical problem for emergency management and generator operators, when their stored fuel may not be of sufficient quality to support a critical generator running at even 50% load. What's going to happen when they need full load from that generator in an emergency?

The whole issue of stabilization and storage is a bigger issue for diesel than for gasoline because it is much more common to store diesel fuel for longer periods of time. Fuel suppliers and industrial customers who store fuel and need to keep it fresh will use an oxidation inhibitor – a fuel stabilizer – to interfere with these harmful reactions and keep the fuel fresh. Consumers who store fuel (such as the boat owner who leaves fuel in his tank over the boat's winterization period) are advised to do the same.

WATER BUILD-UP IN STORAGE TANKS IMPACTS STORED FUEL

Water build-up in diesel fuel tanks is a universal problem across the nation. Almost any stored diesel fuel left for any amount of time will end up with water in the bottom of the tank. And given the changes to the properties of ULSD fuels, it's an even bigger issue than in the past.

Water sinks to the bottom of the tank because water is heavier than diesel fuel is. The culprit is the venting of the tank to the outside air. Outside air packed with water vapor travels in and out of the tank. In storage tanks, the water from the air condenses and rolls down the side of the tank when the air cools down in the evening. The common practice of blending low levels of biodiesel in conventional diesel also accelerates water problems, as biodiesel is hygroscopic and migrates toward any water presence in the fuel.

In diesel vehicles, the temperature change comes from hot diesel fuel returning to the tank after being used to cool the injectors. Injectors get hot due to their tremendous pressures. The engine uses diesel fuel circulated from the tank to dissipate some of this heat. The now-hot fuel is then circulated back to the fuel tank. This temperature difference causes water condensation even in this vehicular environment.

So why does it matter? It matters, for the following reasons:

- As noted below, water allowed to accumulate in a tank increases the chance of a microbial infestation – bacteria and fungi which can play havoc with the fuel system.
- Water in a vehicle or boat fuel tank can be sucked up and circulated into the hot injector. When it reaches the hot tip, the water expands in volume by 40x, blowing the injector apart and sidelining the vehicle. Not a good thing when you are stranded and face a repair job.
- Water in fuel accelerates the oxidation and break down of the fuel.
- Water contributes to tank corrosion

All of these are good enough reasons to control the build-up of water in the tank; this is typically done by using some kind of concentrated fuel treatment. Unless the amount of water in the tank is substantial, in which case, the best course of action would be to pump the water out as part of a fuel PM program. Even the best chemical water-controllers for fuel have their limits. The best course of action for you would depend on the size of the tank and amount of water in it. This is where having a knowledgeable partner becomes a real advantage.

MICROBIAL CONTAMINATION

Storage of diesel fuel, especially ultra-low sulfur diesel and diesel fuel with small amount of biodiesel, for long periods of time also makes them more susceptible to contamination by microorganisms like bacteria and fungus. Despite most best efforts, water inevitably collects at the bottom of the tank. This provides the necessary environment for microbes to grow and flourish in fuel – they live at the interface with the water and fuel, and draw their necessary elements and nutrients from both the fuel and water phases. Pretty soon you've got a microbial infestation that produces slimy "mats" which float on top of the fuel. The microbes multiply, excreting acids from their biological processes which both corrode the fuel tank and accelerate the breakdown of the diesel fuel, leaving you with a tank of nasty, poor quality fuel.

Today's ULSD fuels have virtually no natural resistance to microbial growth because of the removal of the fuel sulfur. Sulfur, historically, has functioned to retard microbial growth – they don't like to be around it. While ULSD fuels are much better for the environment, they are extremely prone to microbial growth that may happen very quickly. It is not uncommon to start with a completely clean and sterile fuel storage tank and see evidence of fuel microbial activity within 1-2 months.

As you can guess, microbial contaminations are most common in situations where the fuel is stored for long periods of time, and also more common in marine situations where the fuel tank is around water. How do you know if you've got an infested tank? You'll probably notice rough running and poor performance

Bell Performance, Inc. tel 407-831-5021
1340 Bennett Drive fax 407-331-1125
Longwood, FL 32750
www.bellperformance.net

with your vehicle or boat. Fuel filters will clog more often and (if you have a storage tank you can see the fuel in), you should be able to see slime floating on top of the fuel (along with foul sulfurous odors). All of these are strong indicators that the diesel fuel tank has a microbial problem.

There are a number of fuel additive products that will claim to eliminate microbial infestations from fuel simply by controlling water. This is where the devil is in the details. Once a tank has an active infestation, simply removing the water alone will not disinfect the tank. You could put fresh fuel in the tank, and over time the microbes would come back in full force. To kill an active infestation, you need to use a Biocide product, which acts to actively kill and destroy the bacteria and fungi. Removing water alone will not kill an infestation if it does take root in your fuel. For maximum effectiveness, biocides also need to be added as part of a preventive maintenance protocol where they can be actively circulated into the fuel.

THE VALUE OF FUEL PM FOR BUSINESS DIESEL USERS

The storage problems that ultra-low sulfur diesel fuels experience mean it is more important than ever before for businesses, emergency backup and fuel storage entities to keep preventive maintenance in mind for their fuels. Today's diesel fuels have enough problems that they cannot risk their fuel not performing exactly how they need it, when they need it. There are options available, such as Fuel & Tank Services companies that will partner with them to both solve existing fuel and tank storage problems (like microbial problems, water buildup and sludge or biomass present in storage tanks). The best fuel and tank services partners take a more comprehensive approach to fuel and PM care, bringing to the table the essential hybrid combination of

- Fuel testing (to pinpoint the specific problem)
- Mechanical fuel & tank cleaning (to address the issues that fuel chemicals aren't always best at)
- Effective chemical treatments (because mechanical cleaning can't keep problems away)

Anyone who relies on consistent stored fuel quality to get the job done would be well to keep this in mind.

FUEL PROBLEMS ON THE PERFORMANCE SIDE

The common diesel fuel problems already discussed have mostly to do to how fuel quality changes over time as it sits, waiting to be used. But whether in an emergency situation or just in the course of "doing business", there are other problems that will rear their heads when diesel fuel with subpar quality specs is used. The nice thing for us in this discussion is that many of these effects can have their causes linked back to some of the fuel storage issues we've already talked about. And that means the best ideas and solution for them can be linked back to the same solutions already mentioned – keeping stored fuel healthy and implementing good fuel preventive care, especially with a qualified fuel and tank services partner.

The first performance-related fuel problems that should be considered are the problematic deposits that may be found in certain areas of the engine. Causally, these deposits can be blamed both on degradation of fuels in storage (through instability development or by microbial activity) and on the fundamental changes in fuel quality that have crept in over the last few decades – changes related to the increased use of unstable cracked fuel stocks to make up diesel fuel. These cracked fuel stocks are necessary in order to demand the ever-increasing demands of the market for more diesel (and more gasoline, too. Same problem, there). So while refineries are able to employ these methods to keep up with demand, the diesel fuels they're turning are more likely to cause deposit problems like these.

Bell Performance, Inc. tel 407-831-5021
1340 Bennett Drive fax 407-331-1125
Longwood, FL 32750
www.bellperformance.net

COMBUSTION CHAMBER DEPOSITS

Diesel fuel does not burn as cleanly as gasoline does. This is due in part to diesel being composed of larger, heavier hydrocarbon chain molecules. Larger molecules contain more energy than shorter molecules (because they contain more carbon bonds to break and release heat energy) but they also have a greater chance of not combusting completely. When they don't combust completely, they can form deposits in the combustion chamber. Combustion chamber deposits can also act as both insulators and fuel sponges. Excessive deposits will change the rate at which heat can escape the cylinder, trapping the heat inside and raising temperatures. When this happens, nitrogen oxide emissions (NOx) increase, which are terrible for air quality.

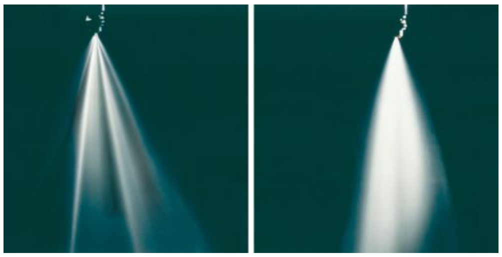
Combustion chamber deposits disrupt ideal combustion and performance by absorbing fuel and by disrupting proper air flow within the cylinder. Typically, these deposits can build up in the piston bowl area. This changes the air flow within the chamber away from the ideal flow designed when the engine was engineered, and this leads the engine away from idea combustion. Absorbing fuel happens because chamber deposits are porous with a network of cracks and crevices that can act as sponges.

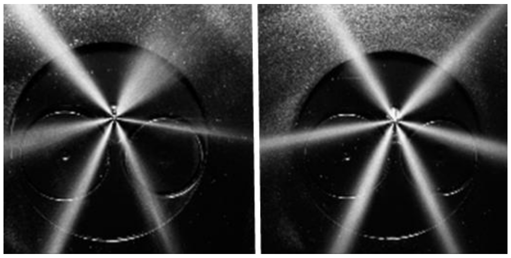
This being said, combustion chambers deposits tend to have a greater effect on engine performance and power than they do on mileage. Vehicular studies do not show combustion chamber deposits to significantly lower fuel economy; injector and valve deposits have a much greater effect on fuel economy.

INJECTOR DEPOSITS

All diesel engines use some form of fuel injection. Most small diesel engines used to use a system called indirect injection (ID1) while larger engines use direct injection (DI). And common rail diesel engines are the dominant technology of today. Most modern passenger car diesels have switched to DI for fuel economy reasons. IDI tends to be smoother and quieter, while DI is more fuel efficient. Whether direct, indirect or common rail, diesel injection technology is light years ahead of what it used to be.

The fuel injector sprays the diesel fuel into hot, compressed air, and the mixture auto-ignites. Efficient metering, atomization and fuel-air mixing are key requirements for good combustion and especially important for low levels of exhaust emissions. Common rail injection systems go several steps further by using a rail-like apparatus to pressurize the injectors and allow the ability to execute multiple injection events in a single stroke, something that previous diesel engine designs found impossible to do.



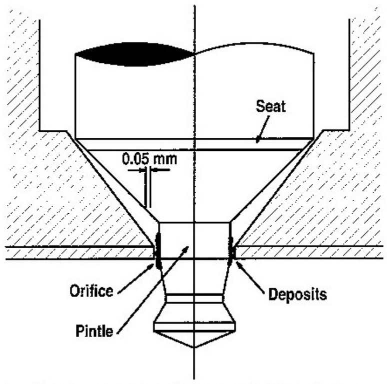


Spray Patterns of Clogged vs Clear Injectors

Modern diesel injectors are designed to exacting standards and form an integral part of the process for optimizing fuel combustion. Their flow characteristics are set to allow a small pilot injection of fuel to initiate combustion, and then inject progressively more fuel into the burning mixture. Such an approach provides a low rate of pressure rise and smoother combustion.

Bell Performance, Inc. tel 407-831-5021
1340 Bennett Drive fax 407-331-1125
Longwood, FL 32750
www.bellperformance.net

Mechanism of Formation of Injector Deposits in Diesel Engines



- Appearance: a uniform varnish type layer with a black brittle nodular layer on top
- Thickness: 6 µm
- Mass: tens of micrograms
- Flow restriction: 26%

Both gasoline and diesel fuels consist of components that boil over a wide temperature range (the diesel range is higher than the gasoline range). When the engine is switched off, fuel remaining in or near the pintle tips mixes together with any remnants of un-burnt engine oil and is subjected to high heat soak temperatures. Such high temperatures lead to the formation of free radical species, and then to a combination of auto-oxidation, chemical rearrangement and degradation of the remaining fuel – and deposits form within the injector.

Diesel fuel does not have the same injector deposit control specifications that gasoline does. Therefore, it is beneficial for the consumer to use an aftermarket detergent fuel treatment to remove these deposits and prevent their formation.

Effect of Deposits on Diesel Injectors

Clean fuel injectors are critical for efficient diesel engine operation. A well dispersed spray pattern maximizes fuel-air mixing, while good atomization ensures rapid, efficient combustion. All diesel fuels, but especially those containing products from refinery conversion processes, have a tendency form a small amount of coke in the annulus of the injector. This coke is believed to be caused by the thermal decomposition of unstable compounds in the fuel. It is such a common problem that injectors are designed to tolerate a certain level of coke. However, many of today's diesel fuels give excessive levels of injector coking, disrupting the fuel spray pattern and degrading atomization.

Higher emissions, noisier engines and a decrease in fuel economy are the result, as shown by controlled vehicle studies. These studies show up to a 15% decrease in city economy and 5% decrease in highway (according to EPA test protocols). For the FTP driving protocol, the results are a 2-11% reduction in fuel economy over the FTP driving protocol, depending on the level of plugging (8-30%).

Another definitive study used fouled injectors collected from two different types of vehicles in the field to show the changes in performance based on sets of injectors with varied average levels of fouling and ranges of fouling. Under the worst conditions of 30% average flow restriction, with a corresponding range

Bell Performance, Inc. **tel** 407-831-5021
1340 Bennett Drive **fax** 407-331-1125
Longwood, FL 32750
www.bellperformance.net

of 30% between the best and worst injectors, the author showed: a 700% increase in hydrocarbon (HC) emissions

In high-fouling injectors, research shows the engine compensates and can cause some cylinders to receive too much fuel and some to receive too little (rich and lean). Once cleaned, a 10.5% improvement results in 40-100 kph acceleration times and a 15.8% improvement in 80-100 kph times. This is confirmed in other parallel vehicle studies, where clogged injectors show a reduction in engine power up to 22% and a 1.3 – 2.8 second penalty in acceleration tests.

INTAKE AND PORT VALVE DEPOSITS

Example showing the effect of detergent additives on inlet valve deposits compared to unadditized fuel.

Poor fuel combustion and stratified diesel fuel which has broken down in storage (because of water buildup, microbial contamination or oxidative breakdown) can lead to deposit formations building up on the valves in the engine. Problems with power loss, decreased fuel economy, startability, driveability demerits, decreased power (increased acceleration times) and increased emissions can all result from this.

Valve deposits can also be a result from a mixture of environmental contaminants and also from mechanical issues in older engines, where engine blow-by (from a worn PCV valve), cylinder blowback (from insufficient ring seal and wear), exhaust gas recirculation (in large transportation truck engines) and lubricating oil, all of those can combine to build up on the valve stems and underside of the valve, forming deposits.

Typically, the biggest ill-effect from these deposits comes when they get large enough to physically block the manifold passage and restrict air and fuel flow into the cylinder. This used to be quite common when carburetors were widespread, and would result in poor acceleration, power, fuel economy and raised emissions. But even low levels of deposit accumulation can affect mileage and emissions, since the deposit can act as a sponge, absorbing fuel into the pores of the deposit, then releasing the fuel through evaporation or desorption (release of absorbed fuel). This disrupts the flow of fuel at the proper timing interval into the cylinder and reduces droplet evaporation efficiency, thus creating an imbalance in the fuel/air mixture into the cylinder. And this means the engine isn't functioning or combusting fuel optimally.

So the typical issues in modern, port fuel-injected engines that have valve deposits are poor driveability (particularly upon cold start-up and during warm-up conditions) and poor emissions performance. Vehicular studies using standard driving procedures like the CRC show a linear correlation between the level of valve deposits and "driveability demerits", which are an index related to how well or poorly the

Bell Performance, Inc. tel 407-831-5021
1340 Bennett Drive fax 407-331-1125
Longwood, FL 32750
www.bellperformance.net

vehicles performance on "driveability". It can be clearly shown that valve deposit buildup affects the vehicle's driving performance and it gets worse the more deposits that build up.

COMBATING DIESEL FUEL DEPOSIT PROBLEMS

Whether these deposits are used by problems in storage or by poor fuel quality in general, the question is how to combat them effectively. A good fuel PM program administered in conjunction with a good fuel & tank services partner should take this into account. The best solutions come down to a two-prong approach:

The first prong is keeping fuel healthy in storage by taking proactive measures to protect fuel stability, remove water and keep storage tanks microbe-free for as long as possible. This minimizes fuel-related deposits that may be traced back to the engine burning unstable fuel sludge and heavy ends that inevitably form when the fuel's storage stability is not sufficiently protected.

The second prong is to make sure the stored fuel that's used has sufficient levels of both cetane and a detergent package.

Stored fuels can lose cetane value over time. Adding cetane improver back into the fuel not only make the engine (and generator and equipment) run at its absolute best, which can be an important factor in both overcoming existing engine deposits and preventing additional ones from forming.

In addition to cetane, a good fuel detergency package delivered in the fuel removes existing deposits from all of the areas already discussed. Today's gasolines already have federally-mandated detergent levels in them when the fuel leaves the refinery. Diesel fuels do not have that requirement. So it would be a best practice to incorporate adding fuel detergent treatment to your fuel, especially as part of a fuel & tank services PM program.

COLD WEATHER PERFORMANCE

Cold weather performance is a big issue for diesel truckers who live and work in cold northern climates, as well as for emergency backup systems that rely on stored diesel fuel to perform in emergencies. Diesel fuel contains complex paraffin wax molecules as part of its composition that serve to contribute to the energy value of the fuel. But when the fuel gets cold, these waxes will come out of solution, making the fuel cloudy. Once out of solution, they stick together to form larger and larger crystals of wax that gel the fuel and plug the fuel filter, shutting down operation.

In these cold climates, a cold flow fuel treatment is an essential tool. These kind of products keep the fuel from gelling by keeping the wax crystals in suspension from sticking together. The crystals stay small enough that they can pass through the fuel filter without a problem, where they get burned off in the combustion chamber with the rest of the fuel.

The previously-mentioned common rail diesel engines have a greater need for cold flow treatment in their fuel than previous engine designs, because the fuel filters catch smaller particles than before. This means these common rail engines will experience service interruptions from fuel gelling at higher temperatures than previously expected.

Bell Performance, Inc. **tel** 407-831-5021
1340 Bennett Drive **fax** 407-331-1125
Longwood, FL 32750
www.bellperformance.net

CONCLUSION

Rudolph Diesel's conception of an engine which combusted fuel based on compression (instead of a spark ignition) is the dominant engine used in heavy industry, long-haul transportation and boating. Consumers who own diesel cars love the outstanding fuel economy. Using a little care and good housekeeping in taking care of your diesel fuel will not leave you disappointed with the results.

Many B2B and stored fuel users might reason they are stretched enough as it is to really undertake the best practices necessary to keep their stored fuel at its best. If that's you, you should strongly consider a fuel & tank services partner. They can do all of this for you, and you may well find that you not only save budgetary dollars, you save headaches as well.