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DIESEL FUEL STORAGE AND HANDLING GUIDE

September 2014

COORDINATING RESEARCH COUNCIL, INC.

5755 NORTH POINT PARKWAY · SUITE 265 · ALPHARETTA, GA 30022

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COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY, SUITE 265
ALPHARETTA, GA 30022
TEL: 678/795-0506 FAX: 678/795-0509
WWW.CRCAO.COM

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Prepared by the

Cleanliness Panel of the Diesel Performance Group
of the Performance Committee

of the

Coordinating Research Council

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1 Introduction

This document provides guidance to users for the storage and handling of diesel fuel. The intent of this document is to provide information that will aid the user to maintain their diesel fuel at acceptable levels of cleanliness during distribution, storage and use. The information presented herein is not comprehensive. The reader is encouraged to seek additional information from other documents and fuel suppliers. Nothing in this document supersedes any relevant federal, state or local regulations. Users should consult appropriate regulators, inspectors, and other experts for specific requirements.

Since the invention of the diesel engine in the late 19th century there has been a continuous need to eliminate contamination from the diesel fuel used by the engine. During that time, engine technology has progressed tremendously which has led to increases in engine speeds and fuel system pressures, the need to control total fuel delivery per stroke, the use of multiple injection events per stroke, injection rate shaping, and other advances. These improvements have resulted in tighter tolerances for moving part control clearances. In combination, these changes make the modern diesel engine one of the most fuel efficient and cleanest burning engines in the world today.

These newer fuel delivery systems and engine technologies require fuel that is as free of contaminants as possible. As a result, on-board fuel filtration has become significantly more robust with both smaller filter micron porosity ratings and higher filtration efficiency requirements. While these improvements in on-board fuel filtration have improved the fuel cleanliness supplied to the fuel injection system, these same changes have resulted in the need for greater sensitivity to the fuel cleanliness delivered to the vehicle or machine. Figure 1 below shows particle erosion in a common rail injector.

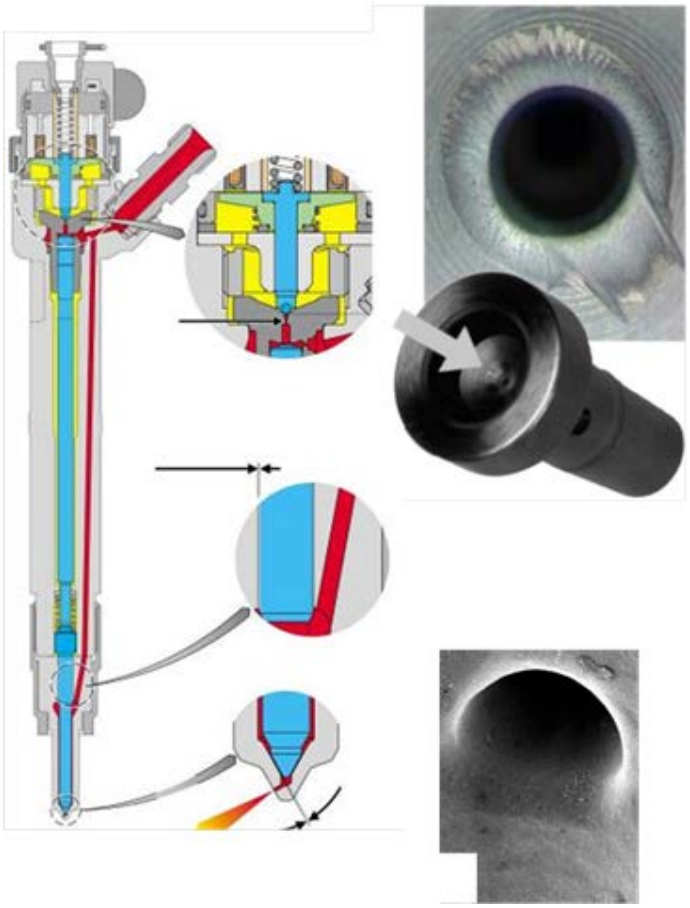


Figure 1: Common rail injector particle erosion[1]

In recent years, industry peer groups have begun placing more emphasis on fuel cleanliness by reducing particulate limits for finished fuels and especially diesel fuel. This is due to the high pressures associated with common rail fuel delivery systems with very tight tolerances found on modern diesel injection equipment.

The Truck and Engine Manufacturers' Association (EMA), along with light and medium duty diesel automotive manufacturers, is pursuing more stringent particulate limits for diesel fuel specifications through ASTM International, an industry standards organization. New particle counting methods, like ASTM D7619[2], use light obscuration techniques to measure particles that are smaller than can be observed by the unassisted human eye (less than 40 microns), and are being considered as viable alternatives to gravimetric measurements of particulate levels in fuels. State agencies are working through the National Conference on Weights and Measures (NCWM) to recommend and promote 10-micron porosity dispenser filters for all products at retail facilities and 30-micron porosity filters for high flow diesel systems such as those found at truck stops[3], all in an effort to ensure cleaner diesel fuel to the end user.

2 Fuel Distribution and Storage Systems

It is often helpful to remember that fuel is subject to change and contamination as it moves through the distribution and storage system network. Diesel fuel distribution starts with production of fuel at the refinery and includes all aspects of storage and delivery until the fuel is ultimately burned in an engine. Once produced at the refinery, diesel fuel is usually maintained in temporary storage on site until it is put into a pipeline for transport. It may also be loaded on other forms of conveyance, such as rail cars, tankers, ships, or barges for transport downstream. The next stop is usually a terminal where it is put in a storage tank prior to delivery to the end user.

It is preferable that terminal tanks should not be “live to the rack” (i.e., loading tanker transport trucks) when product is coming into the tank. If this is not possible, filtration should be implemented between the receiving tank and the rack. Floating suction may be another viable option to minimize particulate transfer from location to location. See API 1640 sections 9.5, 9.7.3 and 13.3 for additional cautions regarding “live to the rack” loading.

Tanker transports receive the finished fuel at the terminal and deliver it to other intermediate storage or directly to the fuel marketer, where the fuel is placed in storage tanks until it is delivered to vehicle or equipment fuel tanks for use in the engine.

The metallurgy of a fuel distribution system is primarily comprised of iron, typically as low carbon or mild carbon steel. These materials, which make up piping, tanks, pumps, and various other pieces of equipment, corrode and form rust as the metal surfaces are exposed to water, oxygen and various other materials contained in the fuel or the air space above the fuel in storage tanks. Corroded metal surfaces liberate rust and other particulate in various sizes and forms that are transported downstream with the movement of products.

The generation and accumulation of particulate and water in the distribution system that gets transferred to other locations are two of the primary sources of contaminants. In addition, free water present at the bottom of storage tanks, at low points along pipeline routes or along the bottom of pipelines themselves, can promote microbial activity that often can result in increased corrosion and particulate generation. The process of pipeline “pigging” or sending a cleaning tool through the pipeline, can also contribute to contamination levels.

Diesel fuel is typically treated with various additives during manufacture at the refinery and then again at product terminals. An excess of fuel additives injected into diesel fuel may lead to the formation of particulates, however due to the cost of additives and regulatory compliance oversight, additives are used judiciously from the point of refining to the final distribution terminal prior to delivery to marketer tanks for sale to the end user. These additives typically include corrosion inhibitors to protect shipping pipelines and storage tanks during movement, drag reducing agents (DRA) to increase pipeline throughput, and cold flow additives to ensure proper flow of products in winter months. Once the diesel is at the distribution terminal it may receive additional additives or an additive package including a dye for “off-highway” applications. See Section 6, Additives, for more information.

The changes in modern vehicle fuel delivery systems described in Section 1 above have further heightened awareness toward contaminants in fuels. As diesel fuel moves through the distribution and storage system, it can pick up contaminants and carry them downstream, even to the end user’s vehicle or equipment. The inclusion of these contaminants can often lead to a fuel not being fit for purpose. A discussion of fuel contaminants is given in Section 4.

3 Storage Tank Considerations

This section provides guidance regarding fuel storage tanks, both above and below ground tanks.

Since corrosion of fuel tank bottoms by accumulated water and sludge can be a significant source of contamination, special internal tank coatings may be used. It is preferable that new above ground storage tanks (AST), or existing AST that are having new bottoms installed, should have the floor and at least the first three feet of the wall internally coated with epoxy, as per API 652[4]. As additional protection, it is recommended that all new steel underground storage tanks (UST) and other small vertical tanks (less than or equal to 30,000 U.S. gallons) have their entire inner surface epoxy coated.

Tank access points (e.g., man-ways, fill tube, nozzles and fittings) are used for tank access and for critical operations conducted while the tank is static or being filled or emptied. These openings allow for the movement of air, product and personnel. If improperly installed or poorly maintained, these openings can be sources for ingress of contaminants resulting in product quality degradation. To minimize contamination:

- All vents should be fitted with screens or breathers designed in such a way to minimize the ingress of contaminants.
- AST's should be equipped with a low point sump and a drain line with a valve that is suitable for removing water and sediment.
- Excessive tank water bottoms should not be permitted in product tanks. All tanks should be constructed with adequate water removing capability. AST "cone up" tank bottom design allows for the collection of free water in the storage tank to be removed at prescribed intervals, minimizing the opportunity for free water transfer downstream. AST "cone down" tank bottom design allows for free water to pass through the tank with the product (often called "drain-dry" tanks). Cone down is often used by pipeline facilities in AST applications. USTs are generally tilted or pitched with the fill side of the tank slightly lower for water detection and removal. However, USTs will often settle over time so the fill side of the tank is no longer the low point. This can lead to a false sense of security when the tank is checked for water at the fill tube tank end as the water will have moved to the opposite end of the tank. Periodic checking both ends of an UST is recommended.
- Fill connections and gauge access points should be provided with tightly fitting covers to prevent entry of water or solid contaminants and evaporative loss. When accessing them, care should be taken to prevent further contamination.

Filtration systems are recommended to reduce particulate or other forms of foreign material contamination. They should be designed with the ability to sample the product both pre- and post-filtration. When filtration is used, it is recommended that the system be appropriately sized for the application utilized, redundant to allow for bypassing a single vessel without interruption to operations, have the ability to monitor differential pressure to ensure system integrity, include air eliminators to reduce risk of internal fire or explosion, be fitted with a pressure or thermal relief valve and include low-point drains for water monitoring and removal. See Section 7 for more information regarding filters and filtration. All strainers, filtration and water separation equipment should be checked and maintained regularly. Daily inspections are encouraged. NOTE: Static electricity may develop in fuel products when filtration systems are used – please refer to API 2003 for specific guidelines.

4 Types of Contaminants

Fuel contaminants come in numerous shapes, sizes and chemistries. They include water, "dirt", microbial growth, solids composed of organic salts, soaps, fuel degradation products, polymers, oxides and

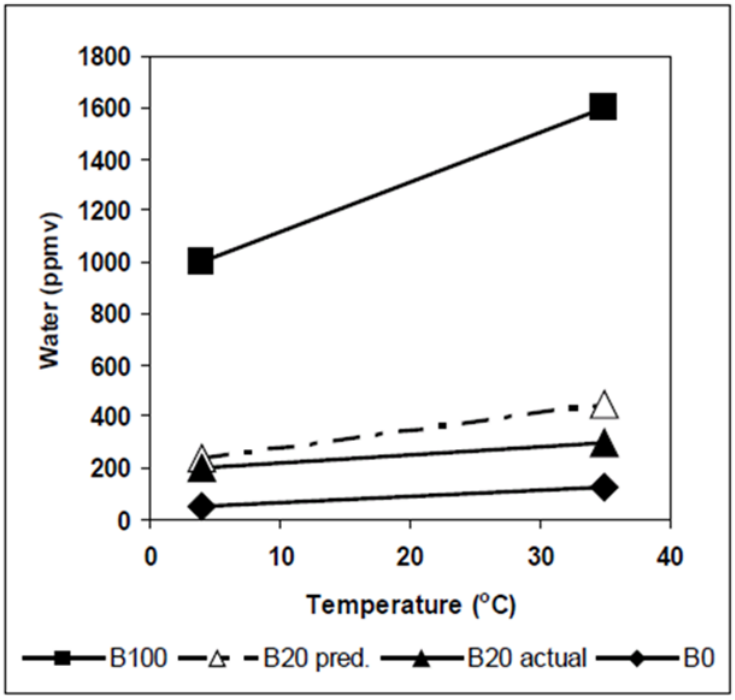
silicates. Regardless of their chemistry and origin, contaminants can contribute to engine deposit formation, erosion-wear and filter plugging. Rather than devoting a separate section to fuel particulates, the topic is covered in context within each form of contamination discussed in this section. Please see Appendix A for further information regarding common fuel contaminants and appropriate countermeasures that can be taken.

Even trace levels of particulate generated in a distribution system can lead to significant accumulation of particulate in tankage over a finite period of time. Consider the following example: if a terminal receives an average of 60,000 barrels per week of product into a specific tank and the material contains on average 10 mg/L particulate, then after one year, this tank would accrue more than nearly 11,000 pounds of external solids. If the average particulates received in the product under the same scenario were reduced to 2 mg/L, then the external solids would drop to roughly 2,200 pounds. A retail storage tank that receives 8,000 gallons weekly would gain 35 pounds per year of solids if the product contains an average of 10 mg/L. At 2 mg/L, the retail tank would accrue 7 pounds per year of solids from the product being delivered.

4.1 Water

Water is the most common contaminant in fuel systems and can lead to many problems if not controlled. Water may enter the fuel or fuel system in various ways, such as part of the refining process, as rain, as ship ballast water or as condensation in storage tanks and equipment. Water can be dissolved in the fuel or suspended as tiny droplets. The amount of water that will dissolve in any given fuel depends on both the composition and temperature of the fuel. In some systems, removal of accumulated water may be sporadic. A build-up of water in a tank can lead to increased corrosion and the potential for greater microbial activity.

If biodiesel is present in the fuel, water can have a more pronounced effect on the diesel fuel. Water is more soluble in a biodiesel blend as compared to a fuel with no biodiesel. Dissolved water in biodiesel can hydrate (or add water molecules to) the fatty acid methyl ester (FAME) molecules. The properties of hydrated FAME are different from those of non-hydrated FAME. Dissolved water in biodiesel, usually in combination with other contaminants, can also lead to hydrolysis of biodiesel, where the molecule is degraded or broken apart, which can allow further reaction with other compounds to form salts, soaps or peroxides. Please see Figure 2 below for water-holding properties of B0 (diesel fuel containing no biodiesel), B20 blends (a blend of 20 percent biodiesel in diesel fuel), and B100 (100 percent biodiesel).



The water shedding characteristics of the diesel blend can be improved by using a fuel performance additive package, in conjunction with good housekeeping practices. However, there may be potential for higher water drop-out in service stations if a fuel that is already water saturated is exposed to a fuel containing an additive package.

Figure 2: Water content at saturation level for B0, B20 and B100[5]

Dissolved water will not change the appearance of the fuel, whereas suspended water (free water) will make the fuel appear cloudy or hazy. Water picked up in one part of the fuel system can drop out in another part, especially as temperature decreases, thus contaminating a tank or low spot in a pipeline. Humid air that enters fuel tanks during normal temperature cycling (breathing) can over time result in water condensation in the tank when the ambient temperature reaches the dew point. This can be more of a problem in high humidity regions. Rain can enter a tank through open fill pipes or man-ways or uncapped vents. Fuel cargo delivered to on-shore tanks by ships can include the ship's ballast water if the water is not stripped off during fuel unloading.

Recognition of the potential routes for water to enter the system is important to the overall quality of the fuel delivered to the end user. The design and development of storage and transfer systems should seek to maximize water and sediment removal and minimize the potential for water to be carried from one point in the distribution system to the next.

If diesel equipment is operated during the heat of the day, warm and humid air will be drawn into the equipment fuel tank. If the tank is left overnight to cool, this moisture may condense and drop out of the fuel, just as in the storage tanks. Topping off the equipment fuel tank to minimize the vapor space at the end of the day's operation will minimize the amount of warm, humid air that remains in the system and thus minimize condensation.

Water in the vehicle fuel system can lead to corrosion, increased metal wear, ice during cold weather, plugged filters or screens, increased degradation of fuel, partial hydrolysis of biodiesel (FAME) in diesel/FAME blends and microbiological growth. Water is also a good solvent for inorganic salts and can contain dissolved acids or other contaminants that can harm the engine. Free water in storage or vehicle tanks can accumulate salts and polar compounds over time and severely impact fuel injection and engine operation. Elimination of water and microbial growth, along with the use of corrosion inhibitor additives, will significantly reduce the amount of corrosion and particulate generation throughout the distribution system.

4.2 Microbial Growth

Many different types of microorganisms are able to use diesel fuel as a food source. These include various species of bacteria and fungi (fungi include yeasts and molds). Aerobic microbes require a source of free oxygen to grow. In contrast, anaerobic microbes will grow only in the complete absence of free oxygen. A third broad category—facultative anaerobes—will live aerobically when oxygen is present and anaerobically when it is not. Like all other life forms, all microbes require the presence of water. Water collects in low points of fuel systems and can become stagnant. This is often where microbiological contamination will occur.

These microbial organisms do not require large amounts of water. They typically range from 0.5 to 3 microns in size and are therefore generally less than 1/1000 the size of a 3 mm thick film of water. This explains why small spots of condensation on the walls of a tank are sufficient to support growth. Viable organisms are found in the air, soil, and even in the fuel, so it is virtually impossible to keep a fuel system sterile without the use of biocides. The effects of these organisms can vary by the type of organism and the volume or mass of organisms present in the system.

The most abundant metabolites produced by microbial communities are low molecular weight organic acids. Although these organic acids are not as aggressive as strong inorganic acids, they can readily react with inorganic anions such as chloride, sulfate, and nitrate to produce strong inorganic acids (hydrochloric, sulfuric and nitric, respectively). These strong inorganic acids can cause corrosion and degrade fuel quality. Moreover, microbes living in the tank bottom water commonly produce detergent-like molecules (i.e., biosurfactants). These biosurfactants generate an inverted emulsion of water in the fuel, distributing water into the fuel-phase and making fuel molecules more readily available as a source of food for the microbes.

The vast majority of microbial contamination in fuel systems is within biofilms. Biofilms are complex structures of sticky, slimy polymeric substances that provide a protective habitat for microbes growing within them. Moreover, biofilms are typically in a state of dynamic stability in which masses of cells are sloughed off, forming biomass clusters as new biofilm is generated.

These microorganism clusters, or flocs, can plug filters or screens or other small orifices in the fuel system. Historically, the fungus Hormoconus resinae was found to be an especially proficient filter/screen-plugging agent. Over the past decade it has been shown that diverse microbes can be as problematic as H. resinae.

The proficiency with which microbes plug screens can be seen in Figure 3 and Figure 4. Additionally, this fungus has a resinous coating while it is growing, which further blocks fuel flow through the colony. Once the colony dies, it loses its resinous coating. It might or might not retain the interwoven structure it had while alive so in either case, the dead fungi are easier to filter from the fuel. The filters or screens might still plug as the dead organisms are removed. However, once the microbiological debris has been filtered out of the fuel, the filter/screen plugging problems should cease. Once a fuel system has been disinfected

adequately, the process of re-colonization and biofilm population restoration can occur in a matter of days. However, it can take considerably more time for the microbial contamination to achieve a mass sufficient to become detrimental to the fuel product or tank structure. The topic of fuel bio deterioration and fuel system microbiology has recently been reviewed[6]. More often in fuel systems the process takes several months to a year, depending on fuel grade, fuel turnover rate and conditions within the fuel system.

Figure 3: Microbial plugged dispenser filter compared to a filter with no microbial contamination[7]

Figure 4: Fuel "rag" layer from diesel bulk storage tank bottom sample[8]

4.3 Wax and Other Organic Compounds

Problem-causing organic compounds are usually of two types: waxes, which are a normal part of diesel fuel, and thermal and oxidative degradation products, which are produced by exposure to oxygen during storage or produced from exposure to high engine temperatures.

Wax can precipitate from the fuel during cold weather and plug filters, screens, and even sharp bends in fuel lines. The most widely utilized specification test to measure this fuel property is the Cloud Point (ASTM D2500[9]), defined as the temperature at which wax particles become visible. The Cloud Point requirement is usually seasonally adjusted and will normally be higher in the summer and lower in the winter.

In addition to cloud point, Cold Filter Plugging Point (CFPP – ASTM D6371), Low Temperature Flow Test (LTFT – ASTM D4539), and Pour Point (ASTM D97) are also utilized to characterize a fuel's cold temperature performance. These tests are important as a fuel purchased in the summer can form excessive wax when exposed to lower winter temperatures. Flow characteristics at colder temperatures can be adjusted by fuel processing changes, blending with No.1 diesel or incorporating cold flow additives.

4.4 Biodiesel Cold Temperature Operability[33]

Biodiesel may also affect cold flow properties and operations in part due to higher viscosity, higher cloud point, or the inclusion of other compounds that adversely affect cold flow operations

There are two different cold temperature performance concerns: handling and operability. Handling, including filterability, is the ability to store, blend and pump B100 or the resulting diesel blend. Operability refers to the use of the diesel blend in a vehicle's fueling system.

As shown in Table 1, the cold flow properties of biodiesel vary with the fatty acid composition of the feedstock. Typical values for biodiesels produced from various feedstocks are shown in the table. However some biodiesel is produced from multiple biodiesel feedstocks.

Table 1: Typical handling properties for biodiesel manufactured from different feedstocks[47]

Feedstock	Cloud Point (^{O}C)	CFPP (^{O}C)	Viscosity (mm^{2}/s at 40^{O}C)
Canola/Rapeseed	-3	-13	4.4
Sunflower	+3	-3	4.4
Soybean	+1	-4	4.0
Coconut	0	-4	2.7
Palm	13	12	4.6
Tallow	16	14	4.8

The cold flow properties of any biodiesel being blended must be understood, especially when biodiesel is blended into a diesel basestock at terminal locations where options to correct the cold temperature performance may be limited.

The second factor influencing cold temperature performance of biodiesel is impurities which can promote the formation of precipitates and deposits. The two main impurities are saturated mono-glycerides and

sterol glucosides. Precipitation from B100 is thought to be associated with the presence of sterol glucosides while precipitation from diesel blends is more often linked to the presence of saturated mono-glycerides.

4.4.1 Sterol Glucosides

Sterol glucosides (SGs) occur naturally in vegetable oils and fats in a soluble (acylated) form. In biodiesel, however, they may be converted to non-acylated SGs. Due to the higher melting points of these SGs (approximately 240°C) and their relative insolubility in B100 or diesel fuel, SGs can be considered to be dispersed solid particles in the FAME product. These dispersed particles may promote the crystallization and co-precipitation of other compounds. The biodiesel manufacturing process, or the pre- and post-processing done as part of the biodiesel production may reduce SG levels to the point where they are no longer a problem.

Even at relatively low concentrations (approximately 35 ppm), SGs may promote the formation of aggregates in biodiesel, exacerbating problems caused by saturated mono-glycerides and other known cold-crystallizing components[10]. This may cause the formation of a cloud-like haze in FAME, even at room temperatures.

If SGs are present and have sufficient time in storage, they are likely to settle to the bottom of storage tanks and vessels. Cold temperatures can accelerate this process and increase the likelihood that SGs will act as nucleating agents for larger agglomerates which will also settle to the bottom of storage tanks and vessels. Draw-down of an unstirred tank that results in these agglomerates being pulled into the delivery system could lead to sudden and unexpected operability problems. As a result, SGs in biodiesel may cause filter blockage at temperatures above the cloud point[11]. For this reason, the contribution of SGs to filter blocking should be considered when addressing filter problems with B100 and diesel blends.

4.4.2 Saturated Mono-glycerides

Saturated mono-glycerides have been identified as one of the problem species for biodiesel blended diesel fuels. The saturated mono-glyceride content of biodiesel will depend on the manufacturing steps taken to reduce their concentration (e.g., distillation, settling). Mono-glycerides have poor solubility in diesel fuel and their solubility is temperature dependent.

4.5 Diesel Fuel Degradation

As diesel fuel ages, it can degrade via thermal and oxidative processes to form polymers and acids[12, 13]. This chemical change is promoted by exposure to high temperature and pressure, oxygen, acids, certain metals such as copper and zinc, or combinations of these. These chemical changes (or reactions) normally result in the formation of both fuel soluble polymers and fuel-insoluble materials, such as gums and particulate. Crosslinking of soluble polymers can generate varnishes as displayed in Figure 5. An example of solid particulate generated by fuel oxidation is shown in Figure 6. Gums can adhere to surfaces, limit fuel flow or clog small clearances in fuel systems causing problems such as injector malfunction or seizures. Particulate can plug fuel filters. Other organic contaminant sources may include coatings and elastomers.

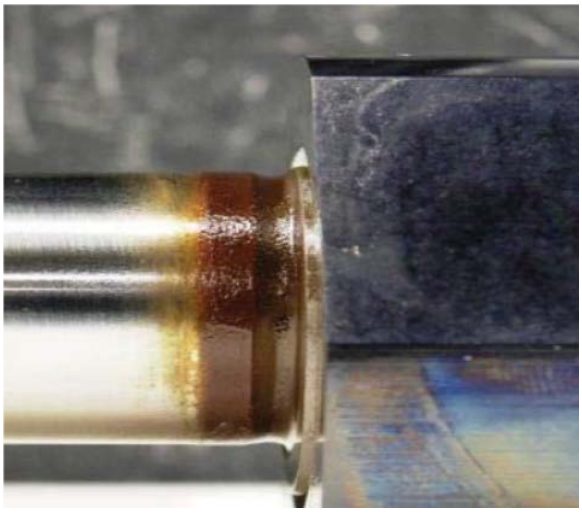


Figure 5: Eccentric shaft of common rail pump with aging polymers[13]

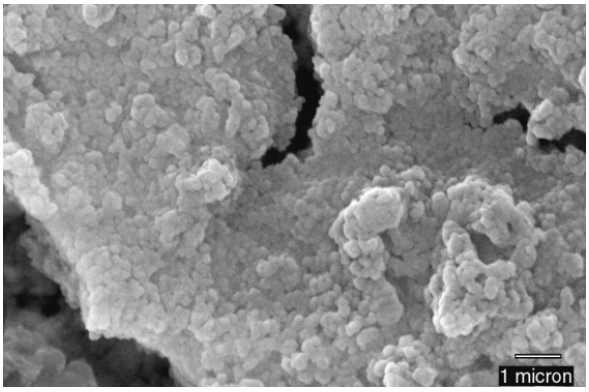


Figure 6: Particulate formed by the degradation of diesel fuel[14]

Besides polymers, acids can also be generated by fuel oxidation[13, 15]. These acids often consist of mixtures of formic acid and other low molecular weight acids. They are also soluble in fuel and can easily form soap precipitates if reacted with any metal ions present as fuel contamination or generated from metal surface oxidation. Typical deposits by soaps of acids are shown in Figure 7.

Figure 7: Metal housing of common rail pump with iron formate deposits[16]

4.6 Inorganic Compounds

Inorganic compounds include rust, other metals, dirt, gravel, sand, salt and similar contaminants. Some of these contaminants, such as rust, may form in storage tanks or distribution system pipes. Others, such as sand or abrasive dust particles, may be carried in with new fuel or may enter through any opening, such as when the fill pipe is open. These materials can result in blocked filters, contribute to tank corrosion, cause wear and/or promote areas for microbial activity to thrive.

Fuel contamination with sodium, calcium and other metal cations can have many different sources, such as:

- Residue from ballast water after sea transportation
- Refinery salt carry over during removal of water from diesel fuel (salt driers)
- Refinery caustic neutralization
- Insufficient catalyst removal (sodium hydroxide/methanolate) during biodiesel production
- Use of alkali metals for hydrogen removal during desulphurization
- Sodium based corrosion inhibitor additive for pipeline protection
- De-icing compounds such as sodium and calcium chloride
- Used lubricating oil blended into fuel
- Engine oil lubricated fuel pumps

The unintended carry-over of sodium should be minimized by elimination of sodium contamination sources which can be determined by an effective monitoring process. Fuel contamination may also occur through vehicle tank ventilation or air intake. Sodium chloride crystal formation on injector valve needle is shown in Figure 8.

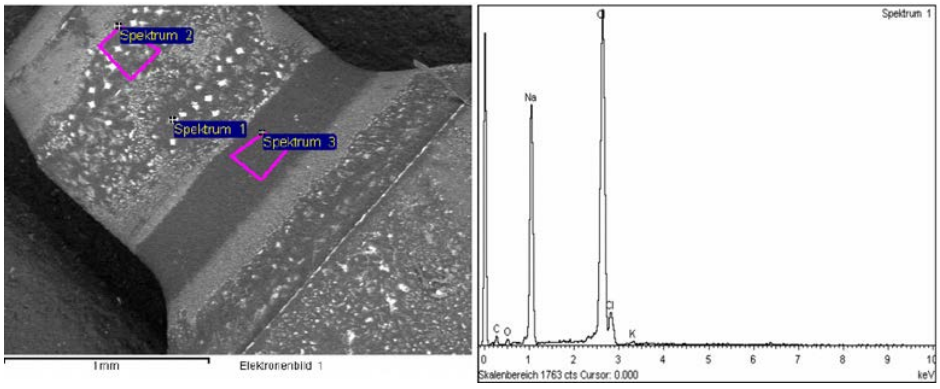


Figure 8: Injector valve needle with crystalline sodium chloride[13]

Other metal ions of concern are zinc, lead and copper. Galvanized storage tanks, piping and terne coated vehicle tanks have led to serious field issues in the past. Zinc has a tendency to accumulate in spray-holes and contribute to nozzle coking. Lead (a component of terne plating) is attacked by fuel acids and forms soap precipitates. Copper may catalytically accelerate fuel oxidation and promote deposition of solids. Non-ferrous metals and their alloys should be excluded from use in fuel pipes and storage tanks and in the entire vehicle fuel system.

5 Fuel System Corrosion

The presence of water, microbial activity and a lack of sustaining corrosion inhibition can all lead to formation of corrosion products in fuel distribution systems. The carbon steel predominantly used in tanks and piping form iron oxides and iron oxyhydroxides (types of iron rust) when the metal surfaces come in contact with water and/or water containing dissolved oxygen. Corrosion inhibitor additives are used to coat the metal surface of the tanks and piping to minimize contact with water and reduce the opportunity for corrosion.

In the United States, the change from Low Sulfur Diesel (LSD) to Ultra Low Sulfur Diesel (ULSD) and its associated handling since 2006 have led to increased fuel field problems[17]. The increased use of FAME biodiesel blends has also contributed to higher incidences of corrosion in fuel systems, due in part to biodiesel's greater affinity for water, a higher susceptibility to microbial activity, and an increased solvency effect on pre-existing deposits. As of this document's publication (2014), CRC have on-going work in this area.

Microbiologically influenced corrosion, as evidenced by the presence of low molecular weight acids and low pH fuel (similar to that found in retail USTs) has also been found in some product terminal and refinery storage tanks[18]. These conditions not only lead to problematic fuel, but can also cause damage to distribution assets, potentially resulting in expensive repairs. See Figure 9 below.

Figure 9: Microbially influenced corrosion of fuel storage and dispensing systems (Sources in clockwise order: Marathon Petroleum, Fuel Quality Services, Fuel Quality Services, Fuel Quality Services, Steel Tank Institute)

Reports of corrosion in vehicle fuel injection systems have also begun surfacing with diesel engine manufacturers. Some claim that a majority of their fuel injector malfunctions are due to corrosive deposits which are increasing.

Figure 10: Common rail fuel system corrosion (photos courtesy of anonymous OEM)

Today's modern HPCR (high pressure common rail) fuel injection systems have very tight metal-to-metal clearances (as small as two microns). These systems can't tolerate even trace amounts of dirt, particulate or corrosion related particles. In some cases, these particles or deposits have caused over-fuelling conditions, which can lead to severe engine damage.

Corrosion can also be caused by the presence of salts, caustic and other contaminants that get passed downstream or are created in distribution and storage systems. Sodium levels exceeding 0.1 percent in diesel tank water bottom samples have been found in many areas of the United States[19]. While this sodium can come from a variety of sources, its presence can lead to steel corrosion and to fuel soap formation. Soap formation occurs when acidic components such as oxidized fuel, some acidic additives (e.g., mono-acid lubricity improvers, etc.) combine with sodium, calcium or other cations to form soaps. If these soaps are formed from inhibitors, the fuel's corrosion protection can be lessened which can lead to further corrosion problems.

Corrosion inhibitors are depleted as fuel passes from the refinery, through pipelines, terminal and retail tanks[20]. This degradation is fairly normal and is to be somewhat expected. Some diesel engine manufacturers believe that existing fuel specifications should include ferrous corrosion requirements to help prevent corrosion problems, so that pipelines, tanks, dispensing equipment and customer vehicles receive the protection they need.

In order to limit corrosion, inhibitor additive is typically added to fuel at the refinery. This is mostly in an effort to protect pipelines and storage tanks as pipeline companies generally require proof that fuel is not corrosive prior to acceptance. Information exists showing that terminal and/or retail fuel systems may experience corrosion[18]. As a result, secondary or terminal addition of corrosion inhibitor may be needed to protect the entire distribution system as well as the tank owner and vehicle customers.

Fuel system corrosion can be controlled with the proper combination of preventative maintenance, proper housekeeping and biocide use where microbial growth has been found. Much of the fuel related corrosion problems are caused by the presence of water. It is common to find water in any fuel storage system no matter how good housekeeping practices are. Water can lead to a whole host of problems including corrosion.

Fuel tanks must breathe and condensation typically occurs in all storage tanks to some degree. Water can come in with fuel and can be entrained in fuel as it passes through the refining and distribution

process. Fuel tends to be warmer in these systems and therefore can dissolve more water. As it gets to the end user—often a cooler UST—the lower temperature causes the dissolved water to fall out. Water is also an excellent solvent for many different types of contaminants including salts such as sodium chloride, which can lead to additional problems.

6 Additives

The focus of this section is on those fuel additives that help keep fuel and fuel systems clean and/or prevent damage to the distribution system and vehicle equipment. Fuel additives are an important part of finished fuel and are used to convert unfinished fuel into useable fuel as well as to help keep fuel stable. From the moment that fuel components are made and blended at the refinery, additives are incorporated into their manufacture, distribution/storage and end use. Additives injected into diesel may include, but are not limited to, anti-oxidants, corrosion inhibitor, cold flow improvers, lubricity improvers, cetane improvers, and conductivity improvers. Refinery fuel additives give refiners more flexibility in manufacturing fuel: corrosion inhibitors give fuel anti-rusting protection, anti-oxidants keep fuel from degrading by improving their oxidation stability, and low cetane stocks can be improved with cetane improver. Other additives such as cold flow improvers are added at refineries to allow diesel fuel to meet important pipeline entrance specifications and vehicle cold operability requirements.

Drag-reducing additives (DRA) are typically long chain polymers added during pipeline transportation to allow fuel to travel through these systems faster, thereby increasing pipeline throughput. There has been some concern over the use of DRA in pipelines. If the DRA is completely dissolved, some shearing will occur during movement down the pipeline. Going through pipeline pumps will completely shear it down. Even with shearing, the size of the polymer can still be many orders of magnitude larger than diesel molecules. However, the size is sufficiently small enough so that operational impact is typically not seen when the DRA polymer is completely sheared. In rare cases, if the additive fails to dissolve in time, insufficient shearing by mainline pumps may result leaving polymer fragments which show “stringy” behavior on filter surfaces and which also reduce filter throughput (see Figure 11). This has been called “reluctant fraction” behavior.

Figure 11: Unsheared DRA (left) and DRA blocking retail filter media (right)[7]

Surface active additives with the exception of corrosion inhibitors are not allowed in fuel during pipeline transportation as these additives can “trail back” into the following fuel in the pipeline. If the following or “trailing” fuel is aviation jet fuel, the additives, including corrosion inhibitors, can cause jet fuel to fail tests for water separating ability. For this reason, lubricity additives typically are added at the product distribution terminal.

Cold flow improvers may also be added at the terminal, usually during the winter season. These additives keep wax crystals—formed as fuel temperature is lowered—from agglomerating into larger, filter blocking crystals.

It is important to note that some fuel additives are more reactive than others, especially acidic additives (e.g., fatty acids such as mono acid lubricity improver or certain types of corrosion inhibitors) that can react with caustic water or other sources of cations such as sodium chloride salt to form soaps[21]. When soaps form, additive protection can be lessened. Instead of providing corrosion or lubricity protection, the reacted product becomes inert, but is still capable of blocking filters and causing injection system deposits. Generally, these reactions are limited unless excursions of excessive levels of acidic additives are combined with caustic or salts (which provide available cations).

Fuel solubility and pH may also determine whether these soaps are fuel soluble or not. Some additive manufacturers offer non-reactive “synthetic” or non-acidic additives to counteract this. Studies have shown that even at high levels, these additives don’t react to form soaps[20].

Additive interaction needs to be fully understood or there could be unintended consequences. This includes after-market additive usage. For example, certain types of corrosion inhibitors have been implicated in fuel injection system problems. It is important to note however, that corrosion inhibitors are necessary to prevent other problems and typically are only used at very low levels (e.g., 5–10 ppm) and are thus unlikely to cause problems unless additive excursions occur in the presence of other contaminants such as sodium. Acidic additives can also react with other additives like Polyisobutylene Succinimides (PIBSI) detergents though this is less understood[22].

7 Filters and Filtration

Many types of filters exist for removing contaminants from diesel fuel. Typically, diesel fuel is not filtered until it gets to the point of delivery to the end user, though some refiners and/or distributors may filter fuel upstream of the end user. Almost all service station diesel fuel is filtered today. Historically, the standard micron porosity rating for diesel dispenser filters has been 30 microns (nominal) rating. Studies have shown[21, 23] that the use of such coarse filters does little to clean up diesel fuel. They are merely protection to catch bigger pieces of debris, such as coarser rust particles or sand.

In recent years, many retailers have moved to 10-micron porosity filters. Most high flow dispensers, such as those used at truck stops, still use 30-micron porosity filters due to flow rate concerns. As of 2014, NCWM is considering a filtration recommendation of nominal 10-micron porosity filters for passenger car and light duty diesel dispensers at service stations[3].

Modern high-pressure, common-rail fuel systems (HPCR) have very small metal-to-metal control clearances (sometimes as low as 2 microns) in order to maintain the high pressures generated in the systems. In order to protect these HPCR systems from metal scoring or other damage, fine filtration of 4 microns or better should be used on the vehicle equipment itself.

Traditionally, diesel fuel cleanliness was measured in mass of particles per unit volume. However, most Original Equipment Manufacturers (OEMs) now require some level of particle counting as a measure of fuel cleanliness. The advantage of particle counting is that the results provide a particle size distribution,

not just the total mass of the particles. As such, particle counting is a more specific measure of fuel cleanliness and the potential of fuel contaminants to cause fuel system damage.

As an example of the increased emphasis on fuel cleanliness and particle size, the World Wide Fuel Charter specification[24] now calls for a minimum fuel dispenser cleanliness level of 18/16/13 per ISO Code 4406 (as delivered to the equipment fuel tank). The ISO code identifies a certain number of particles per milliliter at given size ranges. To achieve the cleanliness level cited in the WWFC, less than 10 micron porosity dispenser filters will likely be required. Please see Appendix B for additional information regarding ISO Code 4406-1999.

Once the desired fuel cleanliness is known, one must determine the ability of their fuel filter(s) to deliver fuel of that cleanliness. Fuel filter ratings are usually a combination of porosity (most often stated in microns) and efficiency. Both are needed to fully assess the filter effectiveness. For example, a 75 percent efficient at 10-micron porosity filter means simply that on average 75 percent of particles 10-micron and larger will be removed from the product as it flows through the filter media. Filters with 95 percent or better efficiency are recommended for maximum particulate removal.

Some filters are “particulate only” filters. They are designed to remove solids and semi-solids that will occlude on the media. These filters will generally not remove water from the fuel passing through them. Some fuel filters also remove free water by coalescing it or by using water absorbing filter media. In coalescing, small droplets of water collect on water repellant media until they form large water droplets which fall to the bottom of the filter where it can then be removed through a drain or some other means. Water absorbing type filters use a Super Absorbent Polymer (SAP) filter media, laminated to a support, to absorb water. The SAP swells upon contact with water, which increases the differential pressure across the filter, and either significantly slows or stops flow altogether. Many water-absorbing type filters can be used for both diesel and diesel/biodiesel blends. Water absorbing filters are available with particulate filtration capability.

Some contaminant level is to be expected in all fuels; however premature filter plugging can lead to slow dispensing, fuel starvation, expensive equipment downtime and other problems.

8 Fuel Specifications

An industry organization often referenced by entities when setting fuel requirements is ASTM International. When considering ASTM specifications, some items must be noted:

- ASTM specifications are written as a basis for agreement between a seller and a purchaser. As such, when both seller and purchaser agree, there can be flexibility regarding where specific parameter limits should apply.
- Generally, fuel specifications are applied at the point of transfer from seller to end user. The intent is to assure that the end user receives fuel of acceptable quality. However, in the period from fuel manufacture to end use, the fuel may actually change custody several times. At each point of custody transfer, some specification parameters may be waived or modified. For example, the lubricity limits for D975 diesel are not enforced until the fuel is ready to be delivered to a final customer. Modified specifications, such as reduced sulfur limits like those imposed by pipeline companies, to ensure that the material being transported meets the requirements once delivered may be instituted.
- The “Workmanship” clause in D975[15], D6751[25], and D7467[26] states “The diesel fuel shall be visually free of undissolved water, sediment, and suspended matter.” It is difficult to enforce this requirement throughout the entire fuel distribution system. A tank bottom sample may not pass the workmanship requirement; however, a retail dispenser sample is expected to pass.

- While the workmanship requirement is qualitative, it remains a very useful and sensitive assessment of fuel quality. The current quantitative requirement is a maximum of 0.05 volume percentage for sediment and water by bottoms, sediment and water (BS&W) centrifuge testing. The BS&W test (D2709) is archaic and generally provides little useful information. A given fuel will fail the workmanship requirement well before it exceeds the maximum limits of the BS&W test.
- ASTM diesel specifications of the future will likely contain both water and particulate limits with the particulate limit likely based on the ISO ratings discussed in Section 7, Filtration, and Appendix B. Currently in 2014, non-mandatory language referring to these limits is being considered.

The Canadian standards for diesel fuel[27] limit BS&W to 0.02 volume percentage maximum, compared to 0.05 volume percentage for ASTM. The Canadian specifications use 4°C (39°F) as the test temperature to conduct the visual haze rating for winter diesel fuel and 15°C (59°F) for summer diesel. The ASTM D975 diesel specifications do not refer to haze rating as a requirement. In the United States, the visual haze rating is typically conducted at 25°C (77°F) or 21°C (70°F) year round.

9 Housekeeping Guidelines

In order to ensure good performance, diesel fuel should be properly cared for during delivery, storage and dispensing of the fuel. Some general guidelines for helping to ensure good fuel quality during storage and handling are shown as follows.

Tank fill areas should be kept clean and dry. Tank bottom water level should be verified by physically "sticking" the tank with water paste both before and 30 minutes after delivery. Automatic tank gauging devices (e.g., Veeder-Root) should not be relied on exclusively for accurate water readings as they typically don't measure less than ¾" of water. Delivery hoses/connectors should be kept clean and dry. A simple "White Bucket Test"[28], commonly used by the aviation industry, is one option to determine whether water or dirt is present in the fuel before it is off-loaded into the storage tank.

All tank openings should have good seals to prevent water or other contaminant ingress. Fill wells should always be slightly above grade to prevent water/contaminant intrusion. Plungers in fill wells should never be depressed—these wells should be pumped out of excess fuel/water mixtures. Ideally, fuel dispensing into vehicles should be halted while fuel is received into storage tanks whenever practical. This helps limit any excessive dirt/water, stirred up during fuel delivery, from getting into vehicles.

Storage tanks should be kept as full as possible. Less air in tanks minimizes water condensation and slows fuel oxidation/degradation reactions[13]. Storage tanks should be kept as cool as possible. This practice helps to slow the degradation reactions associated with the heating of diesel fuel. For ASTs, this can be accomplished by painting the tanks white to reflect the heat associated with exposure to the sun. For USTs, the cool temperatures associated with the lower depths of the ground facilitate this cooling effect. Storage tanks or fuel transfer lines within close proximity of the engine or engine exhaust should be insulated from heat sources.

Active tank water management should be required. Both ASTs and USTs should be as "water-free" as possible. Setting a requirement of having no water in the tank is impractical. However, water should be monitored frequently and be pumped out as soon as possible. As mentioned previously, water is a good solvent for contaminants and can also lead to microbial growth and corrosion problems, so minimizing water content will minimize these problems as well.

Tanks should be vented properly to the atmosphere. Vent caps should be in good condition and not cracked or missing. Consider a desiccant type vent-breather to minimize the amount of water condensed from humid air. Diesel fuel tanks should never share a common vent line with gasoline storage tanks.

This can allow for higher pressure gasoline or gasoline-ethanol vapors to migrate into the diesel fuel and dramatically lower the diesel flash point to dangerous levels. It can also provide ethanol which is a food source for microbes that can cause corrosion[18].

USTs should be tested weekly for water levels by physically “sticking” the tank with water paste. If the “tilt” of the tank is known then the appropriate end of the tank should be tested periodically for the presence of water. If the tank tilt is unknown then periodically testing both ends of the tank for water is recommended.

Tank bottoms should be sampled monthly for visual clarity and at least annually for microbiological contamination, more frequently if microbial activity is found or there is evidence downstream. Simple, easy-to-run culture tests are readily available. Tanks should also be periodically tested for integrity according to internal policies and/or local, state or Federal regulations.

Dispensers should be kept clean and in good working order, especially around the nozzle area. Fuel dispensers should be fitted with a maximum of 10-micron porosity (nominal) water-absorbing type filter from a reputable manufacturer[3]. Thirty (30) micron filters are still commonplace in diesel filtration. As mentioned above, however, recent studies[21, 23] have shown that they do not make fuel clean enough for modern diesel injection systems. Dispenser filters are not meant to be the last filter before fuel sees an engine. Instead, the job of final engine filtration is meant to be handled by more stringent “on-board” engine filters. When flow rates drop to approximately 50–60 percent of normal rates, filters should be changed. Dispenser samples (1 quart or liter) should be visually observed in a transparent container on a weekly basis. Samples should be free of dirt and water (known as “clear and bright”). Filter plugging is only one cause of dispenser flow restriction (see discussion of fuel corrosivity and component failure above). By observing flow rates immediately before and after filter replacement, maintenance personnel can determine if slow flow symptoms were caused by filter plugging or other system component failure.

If microbial activity is found during routine testing, treatment with biocide is recommended. It is desirable to have the post-treatment test showing no microbial activity. A negative result means there was an effective kill. However, if the post-treatment test is positive then vendor recommendations should be followed for an increased biocide dosage. If problems are recurrent in a given tank, upstream sources should be investigated. Proper housekeeping such as drawing off excessive water and maintaining storage vessel and piping seals and joints for integrity all help to keep fuel water and microbe free. When water is minimized, biological contamination problems are minimized as well.

Consideration should be given to the installation of filters with 95 percent efficiency where there is truck, rail, pipeline or marine movement. The preference is that filters be of the coalescing type and particulate removing (10-micron). They should be constructed so that one set remains in service while the other is being changed out.

When high levels of water or sediment are identified, the tank should be isolated and allowed to settle at a rate of 1 hour per 1 foot of product to suction or 24 hours, whichever is less. As mentioned above, tank linings are preferred for all new installations. Tanks that are already in service may be lined during API 653 inspections[29]. It is preferable that tanks less than or equal to 30,000 gallons in capacity be completely lined.

Vents should have screens, filters and breathers installed to minimize particulate and other airborne contaminants from being introduced into fuel storage tanks.

10 Concluding Remarks

This guide is a living document and is subject to periodic revision as appropriate. As more research on Diesel Fuel Storage and Handling Guide related topics are completed and we learn more, the guide will be updated with the newer, relevant information. Suggestions for improving the document should be directed to the Diesel Performance Group Cleanliness Panel leader, the Coordinating Research Council.

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12 Appendix

1. “Cummins Filter Plugging Contaminants”, Cummins Engine Company, 2014
2. ISO 4406 Particulate Cleanliness Chart, Adapted excerpt is taken from ISO 4406:1999, Table 1 on page 3, with the permission of ANSI on behalf of ISO. © ISO 2014. All rights reserved

12.1 Appendix A – Typical Contaminants and Countermeasures

Contaminant	Carboxylate soap (metal carboxylate soap)
Symptom(s)	High restriction, plugged filters
Field Test Method(s)	Delta-pressure gauge across filter head, if possible
Laboratory Test Method(s)	Flow vs. Restriction Test, ICP ASTM D5185 modified, ASTM D7111 or similar
Source(s)	a) Water bottoms b) Acidic additives such as pipeline corrosion inhibitors, some lubricity improvers, etc. c) Various metals in incoming supply fuel or introduced within the engine can help generate carboxylates d) Tank ventilation opening arranged in location conducive for contamination entering fuel tank (e.g., spray area of wheels) e) Carry-over or spills from refinery salt driers
Contamination level that may cause problems	>200 ppm of water to stage 1 filter; metals content goal is <0.1 ppm of Na, K, Ca, Mg or Zn or no trace or detectable amount. Existing test method minimums are 0.21, 0.19, 0.10, 0.10, and 0.09 respectively per ASTM D7111. It is anticipated that future methods will be capable of 0.1 ppm or less. ICP-MS and other non-standard tests are already capable of these lower numbers.
Countermeasures or Corrective Actions	a) Drain water bottoms and periodic inspection and maintenance of fuel storage, fuel delivery and equipment fuel tanks b) Work with fuel supplier to ensure compatible corrosion inhibitor usage and that metal-free fuel is provided c) Use approved detergent/dispersant additives d) Replacement of galvanized wetted surfaces/components (supply tanks, plumbing, fittings, etc.) to eliminate possible zinc contamination.

Contaminant	Wax
Symptom(s)	cold operation plugging, longer starting time
Field Test Method(s)	Potential field visual inspection (cloudy), warm fuel or filter to confirm/solve wax plugging issue.
Laboratory Test Method(s)	Cloud Point Test (ASTM D2500, ASTM D5773), Cold Filter Plugging Point (D6371), LTFT (ASTM D4539)
Source(s)	Long chain n-paraffin in fuel, use of summer blend fuel in winter
Contamination level that may cause problems	Cloud point, CFPP or LTFT of fuel above ambient operating temperature could cause issues.

Countermeasures or Corrective Actions	Use of: cold flow improver additive (preemptively), suitable winter blend fuel, approved fuel/filter heaters. Replace filters and keep warm.
Contaminant	Soft and hard particles
Symptom(s)	Contaminant cakes on filters, high restriction
Field Test Method(s)	Visual inspection (if particles are visible, fuel cleanliness is above required level), field particle counting
Laboratory Test Method(s)	Laser Optical Particle Count (ASTM D7619)
Source(s)	Water contamination can bring in dirt/rust Dust contaminated supply fuels Application environment (dust ingested thru fuel tank vent) Switch of fuel type can result in fuel tank debris to be loosened and migrate to filters
Contamination level that may cause problems	Dispensed fuel contamination levels above 18/16/13 per ISO 4406 (reference Appendix B)
Countermeasures or Corrective Actions	Pre-filter (bulk tank filtration) Routine tank inspection and cleaning Fuel tank vent filtration Higher capacity filters Multi-stage filtration

Contaminant	Algae, bacteria and fungi
Symptom(s)	Clear, green, black or brown slime, foul smell (hydrogen sulfide), rotten egg smell
Field Test Method(s)	Laboratory analysis
Laboratory Test Method(s) and Guides	ATP Test (ASTM D7463, D7687), ASTM D6469, , standard culture tests
Source(s)	Water in fuel tank bottoms, warm conditions, lack of tank maintenance, long storage and environment
Contamination level that may cause problems	Any non-dissolved water
Countermeasures or Corrective Actions	Drain free water frequently, sloped storage tanks with petcock drains, desiccant tank vent, tank cleanup, biocides should not be used routinely, annual inspection/routine tank maintenance, tank ventilation and filtration

Contaminant	Corrosion products due to water in fuel (Note: water typically does not intrinsically plug filters but can contribute by aiding the other contaminants to develop and collect)
Symptom(s)	Corrosion, water in fuel sensor alerts, water separation canister visually full, plugged filters, frozen fuel lines
Field Test Method(s)	Fuel Suitability Test (ISO 4020 older version) Clear and bright standard for visual check of fuel ASTM D4176 bar chart test
Laboratory Test Method(s)	Steel Corrosion Test (ASTM D665, D7548, NACE TM0172), Karl Fischer test method for water content, (ASTM D6304, E203),
Source(s)	Ship ballasts, ambient conditions including in-tank condensation of water vapor due to temperature cycling or changes, improper fuel tank ventilation, lack of fuel tank maintenance, fuel supply already contaminated, poor fuel tank construction
Contamination level that may cause problems	>200 ppm to Stage 1 fuel filter worse than NACE B+ (e.g. B, C, D, E rating)
Countermeasures or Corrective Actions	Drain free water frequently, slope storage tanks with petcock drains, desiccant and filtered tank ventilation, minimum annual inspection, consult fuel supplier, upgrade of filtration to larger capacity and higher efficiency

Contaminant	Lube oil
Symptom(s)	Dark brown or black appearance of filter media and fuel
Field Test Method(s)	Visual
Laboratory Test Method(s)	ICP (ASTM D5185, D7111 or similar) Filter Blocking Tendency Test (ASTM D2068)
Source(s)	Improper use of oil by end-user Used oil burn systems Oil lubricated fuel pumps leaking excessive lube oil into fuel
Contamination level that may cause problems	any level of soot laden lube oil leads to filter plugging
Countermeasures or Corrective Actions	Avoid blending of oil into fuel Repair fuel pump, if excessive lube oil leakage is confirmed

Contaminant	Asphaltenes, carbonaceous particles
Symptom(s)	Premature filter plugging
Field Test Method(s)	Visual inspection
Laboratory Test Method(s)	Test fresh fuel, Thermal Stability (ASTM D6468), PetroOXY Stability (D7545)
Source(s)	Fuel instability from long-term storage (longer than 3 months), erroneous fuel blend
Contamination level that may cause problems	Less than 80% reflectance for D6468 (180 minutes), <60 minutes for D7545
Countermeasures or Corrective Actions	Asphaltene conditioner, fuel stabilizers, anti-oxidants, drain and replace fuel

12.2 Appendix B – ISO 4406 Particulate Cleanliness

ISO 4406 is a standard which measures the number of particles per milliliter in three different particle size ranges: greater than 4 microns, greater than 6 microns and greater than 14 microns. Several different types of optical particle size counters exist with the most popular being the light diffraction or obscuration type such as that used in ASTM D7619, “Standard Test Method for Counting and Sizing Particles in Light and Middle Distillate Fuels and Liquid Bio Fuels by Automatic Particle Counter”.

ISO 4406 Cleanliness

ISO Code	Minimum	Maximum
10	5	10
11	10	20
12	20	40
13	40	80
14	80	160
15	160	320
16	320	640
17	640	1300
18	1300	2500
19	2500	5000
20	5000	10000
21	10000	20000
22	20000	40000
23	40000	80000

Table 1: ISO 4406 fluid cleanliness codes (particles per ml.)

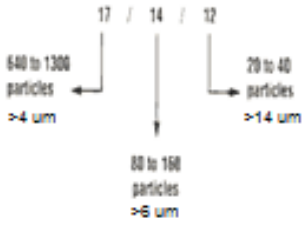

Figure 1: ISO code example

12.3 Appendix C – Authors

Rick Chapman, Innospec Fuel Specialties (Team Leader)

Norm Blizard, Cummins Engine

Ed English, Fuel Quality Services

Roger Gault, Truck & Engine Manufacturers Association (EMA)

Garry Gunter, Phillips 66

Roger Leisenring, KiOR

Russ Lewis, Marathon Petroleum

Tom Livingston, Robert Bosch

Shailesh Lopes, GM Powertrain

Manuch Nikanjam, Chevron

Fred Passman, Biodeterioration Control Services (BCA)

Steve Westbrook, Southwest Research Institute (SWRI)