So You Think You Know Diesel

For a marine diesel engine to perform at its best, the fuel it gets must be of suitable type and grade—and completely free of water and contaminants. Easier said than done.

Text and photographs by Steve D'Antonio

Above—*Various diesel fuels are available—low sulfur, ultra-low sulfur, taxed, untaxed—but it's not always possible to tell them apart based on appearance alone. In the United States, for example, red dye is a marker with multiple meanings (see the main text, and the photo caption on page xx).*

Diesel engines require a clean, air-free, reliable supply of fuel. Without it, their safety, reliability, economy, and longevity are compromised. But there's more to meeting that need than simply ensuring a vessel's tanks and filters are clean and the fuel plumbing is sound. While those vital components—filters, tanks, and associated plumbing—and their maintenance can be thought of as a vessel's macro-fuel system, the selection and care of fuel on the molecular *level are equally essential to diesel engine maintenance. For builders and yard operators installing or maintaining diesel engines and fuel supply systems, a solid understanding of* what's in your fuel *is almost as important as knowing* what your fuel's in.

Most engine manufacturers, mechanics, and vessel operators tend to be fanatical about obtaining clean diesel and maintaining a clean fuel system. They don't sweat those details for gasoline engines. Why? Because although all internal-combustion engines require a clean supply of fuel, diesel engines are more sensitive to contamination due to the fuel's *lubricity*. Diesel fuel is quite slippery (if you've ever spilled any on deck or the cabin sole and stepped on it, you know this) thanks to two attributes that involve hydrodynamic and boundary lubrication. The former is the cushion created by any liquid between close-fitting components; in this case, diesel fuel between metal parts. The latter is molecular and involves oxygen, nitrogen, and aromatic compounds adhering to the surface of the metal, creating a film or boundary layer that reduces friction.

If diesel fuel didn't have these properties, then the diesel engine as we know it would not be possible: in order to create the extremely high fuel pressures required for compression ignition, the tolerances for moving parts within the fuel delivery system must be extremely close—a few microns close, depending on the parts.

Cetane is a measure of diesel fuel's "ignitability." In general, the higher the number the better, with anything under 40 usually deemed unacceptable by most engine manufacturers.

Now, all diesel engines work on the compression ignition, or CI, principle, whereas gasoline engines utilize spark ignition, or SI, to achieve combustion. If diesel fuel were robbed of its lubricity, then an engine burning it would quickly wear out, rather than operating for the now-customary thousands, or tens of thousands, of hours. This principle is important for the conventional pump-line-nozzle, or PLN, diesel—the most common type of diesel engine in marine and many automotive applications. It's even more critical for the newest engines, namely: common rail, or CR; and hydraulically actuated electronically controlled unit injection, or HEUI. These fuel-injection systems operate at higher pressures and demand more of the fuel as a lubricant and coolant for the high-pressure pump and injectors.

Gasoline engines that rely on spark ignition don't require the extremely high pressure of a diesel. Consequently, a small amount of air in the delivery lines, while still undesirable, is much less debilitating than the same condition would be to a diesel.

Cetane

At most roadside fuel stations there is typically a choice of three different "grades" of gasoline: regular, something in the middle range, and premium. The grades correspond to an octane rating, which is a measure of gasoline's ability to *resist* auto-ignition and wait for the spark plug to ignite it, rather then be touched off by hot metal or carbon residue in the engine's combustion chamber. Higher-performance, higher-compression-ratio (a measure of how much the engine compresses the fuel/air mixture before it's ignited) gasoline engines typically require higher octane, or premium, fuel to prevent damaging auto-ignition, commonly known as "knocking."

Diesel fuel has a similar grading system. Some roadside diesel pumps are labeled "premium." The difference between unlabeled diesel and premium diesel is the *cetane* number, often called CN. The number may range between 35 and 50, with anything over 45 being considered premium. In addition, premium diesel may—or may not—contain detergents that help keep fuel injectors clean while minimizing carbon deposits on pistons, rings, and valves.

The cetane number is a measure of a diesel fuel's ignition quality and is inversely analogous to gasoline's octane rating. Cetane is a measure of the ease with which diesel fuel auto-ignites; *octane* measures gasoline's resistance to auto-ignition.

Higher-cetane fuel ignites more quickly after injection into the combustion chamber; lower-cetane fuel experiences a longer delay. Running on low-cetane fuel can cause hard starting, smoking, increased noise, rough idling, and the production of more particulate emissions.

Most diesel engine manufacturers specify a minimum cetane number at which their engines should be operated—usually 40. Some technical and sales literature might suggest there is no advantage to running an engine on fuel with a higher cetane number than its minimum requirement. In practice, this may not be true. Even though the engine can run within

A confounding array of sulfur-content placards is often found at the fuel pumps. For current marine *engines, sulfur content is largely inconsequential from a performance standpoint. (New on-road vehicles, however, may be designed to operate on ULSD alone.)*

acceptable parameters at the minimum CN, it won't run as well as it will on high-cetane fuel. Typically, the operator will experience a noticeable improvement in starting, running characteristics, and fuel economy with higher-cetane fuels up to a CN of 50. Beyond that point, there is little or no advantage in performance, or emissions reduction.

Sulfur

Anyone who works on diesel engines or sells diesel fuel or fuel additives is acutely aware of new federal regulations limiting the sulfur content of diesel fuel. During the past 15 years, diesel sold in the United States was permitted to have any one of three levels of sulfur content: 5,000, 500, or 15 parts per million. Those fuels are also referred to as S5000, high sulfur; LSD/S500, low sulfur; and ULSD/S15, ultra-low sulfur. In 1993, 5,000-ppm high-sulfur diesel was phased out in favor of S500 low-sulfur diesel. Since mid-2006 the U.S. Environmental Protection Agency, or EPA, has mandated S15 ultra-low-sulfur diesel for all *on-road* diesel vehicles.

Sulfur dioxide, a by-product of burning sulfur-rich diesel fuel, causes irritation to the lungs and eyes. Also, the gas combines with atmospheric oxygen and water to form atmospheric sulfuric acid, or acid rain. According to the EPA, the new, lower-sulfur standards will cut sulfur-dioxide and nitrogen-oxide emissions by approximately 2.6 million tons each year, while soot and other particulate material will be reduced by 110,000 tons per year.

This change, by the way, means U.S. diesel will match the formulation of diesel currently sold in Europe. As a result, we might see more diesel automobiles marketed in the States, since the quiet, ultra-efficient, smokeless diesels that comprise *60%* of European passenger cars will now have this fuel available to them in the U.S.

Sulfur reduction will enable engine manufacturers to implement exhaust system after-treatment technology that employs catalyst-type emission control devices, such as particulate filters and nitrogen oxide absorbers. Until recently, those filters and absorbers have been unusable, owing to the comparatively high sulfur content found in U.S. diesel. Expect this technology to trickle down into the recreational marine diesel market as emissions standards become progressively more stringent.

Regulations aside, there are a few possible side effects to ULSD that are worth noting. Contrary to popular belief, the sulfur itself is not a lubricant. Instead, the desulfurization process, known as hydrotreating, breaks down some of the fuel's larger hydrocarbon molecules, which leads to reduced lubricity. In theory, this shouldn't be a problem, inasmuch as the refinery or distributor will include a lubricity enhancement additive with the finished product.

To address the lubricity concern, the ASTM International requirement for diesel fuel, D 975, was amended to include a previously unspecified lubricity standard. That will return fuel to the equivalent of its high-sulfur lubricity, or greater. Interestingly, it looks as if the additive may be, in many cases, *bio*diesel. Because biodiesel has natural lubricity higher than that of any petro-diesel, it's well suited for this application.

Every major oil-company rep I spoke with was adamant that user-applied lubricity additives are not needed. Refiners in the U.S. are responsible for supplying fuel that meets the ASTM International standard for diesel fuel, which means it is "fit for purpose" when it leaves the refinery or distribution facility, with no further adulteration required to enhance lubricity.

An additional effect of switching to LSD or ULSD is the possible increase in fuel system leaks. When LSD was introduced in 1993, there was a rash of fuel system leaks, primarily at lift and injection pumps, and in some filter assemblies. The problem? Elastomer seals or O-rings swell in the presence of sulfur. When LSD was introduced into the fuel system, the sulfur leached out of the seals, causing them to shrink and then leak.

During that changeover I recall removing leaking fuel-injection pumps for repair and rebuilding. It appears that this has not been a noticeable problem with the subsequent change to ULSD. Generally, engines that suffered the leaks during the change to LSD were of early-1980s vintage or older; however, it's worth keeping an eye on fuel systems for possible ULSD-induced shrinkage and subsequent leaks.

Finally, although field reports provide conflicting information, it seems that ULSD is capable of supporting an average of between 20 ppm and 40 ppm dissolved water at the molecular level within the fuel. Compare those values with high-sulfur diesel and LSD, which can carry between 50 ppm and 100 ppm. Initially, this may appear to be an improvement, since less water in the fuel is better. Still, one side effect of ULSD is a less-efficient medium for suspending and carrying water out of a vessel's fuel tank to either the engine's combustion chambers, where in such small amounts it is vaporized, or to the water-separating fuel filters. So, running ULSD can lead to more water accumulating at the tank bottom, causing corrosion in metal tanks and a greater likelihood of enhanced biological activity—and the detritus it produces.

And what of off-road and marine applications? LSD/S500 will remain legal and available until some time in 2012.

(The implementation dates for S15 are staggered across different applications, including on-road/highway, off-road, marine, and rail, beginning with the introduction of S500 in 1993 through full S15 compliance for all applications in 2012.)

In practice, the change to ULSD might come well before then for a couple of reasons. Out of convenience, vessel operators may already be purchasing on-road ULSD to fill their tanks, and they may soon find they have no choice between LSD and ULSD even if the former is still legal for a marine engine. That's because refineries, transport pipelines, bulk-fuel transport services, and retailers avoid the complication, wherever possible, of carrying both products. So, if the majority of the market is required to fill up with ULSD, then that's the fuel type that will be readily available to all diesel users.

There are two more concerns in the switch to ULSD: increased solvency, and instances of contamination. Anecdotal evidence has shown that when switching from high sulfur to LSD or ULSD, the frequency of clogged filters increases. One cause of additional contamination during the transition to ULSD is refineries and distributors minimizing storage-tank volumes prior to receiving new fuel, and thus inadvertently introducing sediment—referred to as "tank bottoms"—into the supply stream.

Another cause is the fact that LSD usually contains higher amounts of aromatic and fewer paraffinic compounds than ULSD. Petroleum researchers say the change to fuel containing fewer aromatics and more paraffins may dislodge oxidized fuel and heavy hydrocarbons that collect in fuel tanks over years of service. This loose material can, during the transition from LSD to ULSD, clog filters. Depending on the quantity of accumulated material, the problem may be short-lived; or, in heavily contaminated tanks, it could go on indefinitely.

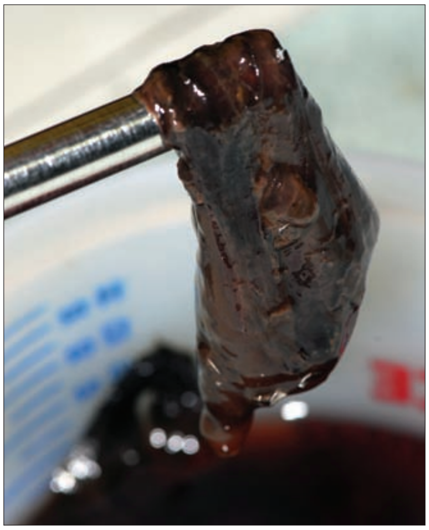
***Top**—In the U.S., red-dye diesel fuel always indicates untaxed fuel. But, owing to a lack of coordination between federal agencies, the dye can sometimes indicate high sulfur content, too. Worse, different agencies specify different dyes. **Bottom**—These filter bowls clearly indicate this vessel has taken on two types of fuel: untaxed (or off road) on the left, and taxed (on road, and most likely low sulfur) on the right.*

A final note on ULSD comes under the heading of rumor control: unlike ethanol-laced gasoline, or E10, and its predecessor MTBE, there is no compatibility problem between LSD and ULSD. The two products can be mixed without concern.

Dye

A confusing cloud of regulations has arisen around diesel fuel. Why? Because both the U.S. Internal Revenue Service and the EPA require the addition of red dye to certain classes of diesel fuel, but for different reasons and at different concentrations. In short, red-dyed diesel is *typically* high in sulfur, and less heavily taxed.

The EPA's stated goal is to dye fuel that's high in sulfur content so that it does not find its way into on-road applications. For its part, the IRS specifies the dye to ensure that tax-exempt, low- or high-sulfur diesel is not used in taxable applications. So, high-sulfur diesel must be dyed red at the refinery to meet EPA regulations. Thus, all *un*dyed diesel fuel is low sulfur, and taxed, while dyed diesel is untaxed, but might be high or low in sulfur. As I said above: a confusing situation; still, I've chosen not to detail here the myriad regulations concerning differing dye concentrations. That information, for those who wish to know it, is available at the EPA's and IRS's respective Web sites.



Left—*A graphic example of biological growth from a marine fuel tank. Most diesel bio-contamination is bacterial; the lack of light inside a typical fuel tank precludes the ability for algae to exist there.* ***Right***—*Sampling and inspecting fuel is the most basic way to ascertain its quality. This sample was taken from the tank of a recreational vessel in service for less than a month. Placed in front of a photographer's slide table, the suspended sediment is clearly visible.*

Contamination

Diesel fuel's lubricity, as discussed at the start of this article, is one of its essential attributes. Contamination with dirt or water simply reduces the fuel's slipperiness. Recall that sulfur reduction also reduces lubricity; that fact actually enhances the effect of contaminants in the fuel. They threaten the finely machined, fitted, and polished components in the high-pressure side of the fuel-delivery system. The injection pump and injectors, or the high-pressure pump in a common-rail system, will suffer from extremely rapid wear and premature failure.

Water contamination and particulate-matter contamination often go hand in hand, since one nearly always leads to the other. Water in a fuel system is an invitation for biological organisms to set up house. Once a colony establishes itself, the by-product is a slimy bio-ooze that quickly clogs filters and, in extreme cases, pickup tubes.

Biological organisms require specific environmental conditions to thrive. (Note that these organisms are bacteria, fungi, and yeast; contrary to popular belief, they are *not* algae.) Those life forms must have water to live in; the carbon in diesel fuel is their main source of food, and oxygen and sulfur are essential for respiration. The interface between diesel fuel and water is the habitat where such bio-colonies flourish. Warm ambient temperatures accelerate their life cycle. In the right conditions, bio-colonies can reproduce at a prodigious rate. A single-cell organism weighing a fraction of an ounce is capable of developing into a bio-colony over an inch (25mm) thick and weighing several pounds in less than 24 hours.

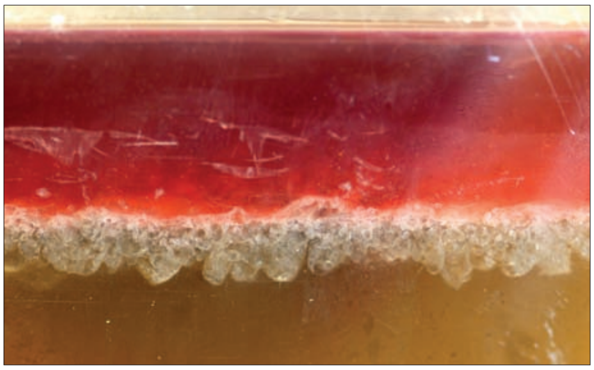
Cold weather kills off most fuel system bio-infestations; but, natural mortality presents its own problems. Season after season, fattened carcasses of those carbon-grazing life forms accumulate at the bottom of the tank, and foul the fuel system when agitated in a seaway. Many a vessel has limped into the yard I managed, after having its tanks shaken up by the short, steep waves of the Chesapeake Bay.

Biological contamination can harm the tank itself, not merely the more delicate fuel pumps and injectors. One of the by-products produced by bio-colonies is hydrogen sulfide, an acidic material that will cause corrosion in aluminum and ferrous tanks. A large bio-carpet that forms on the bottom of a fuel tank is capable of trapping hydrogen sulfide as well as water, and holding it against the tank bottom. This situation almost always leads to severe tank corrosion and, potentially, tank leakage.

Water emulsifiers and bio-extermination additives, while often effective, are a topical approach to biological contamination; they address the symptom, rather than prevent or cure the cause. The best approach to discourage such contamination is to keep water out of the fuel tank from the beginning. Without water, bio-organisms cannot exist.

Other contaminants found in diesel fuel are gum, petroleum residue, and inorganic salts, often collectively referred to as *asphaltine*. These contaminants may be in the fuel as it leaves the refinery, or they might be introduced during transport via pipeline or truck. While fuel is stored, either ashore or in a vessel's tank, microfine particles of *in*organic contamination can begin to bind to each other, forming larger, visible clumps of

Right *and* ***below***—*Biocides can successfully stem or mitigate biological growth in fuel tanks, once it's started. With prevention in mind, note that biological growth can exist only in a fuel tank or system where water is present.*



The water/fuel interface provides a home for biological growth in fuel tanks. This sample was taken from a tank that received diesel grossly contaminated with water. The vessel experienced engine problems almost immediately after getting under way.

black, asphalt-like tar that accumulate on tank bottoms and walls.

Unlike bio-slime, inorganic particles, in addition to clogging filters, are capable of causing rapid, severe wear to piston rings, injectors, injection pumps, and high-pressure pumps. Note that the newer CR and HEUI fuel-delivery systems are more sensitive to all forms of debris than conventionally injected PLN diesels. (These acronyms were explained at the beginning of the article.)

Ordinary water that contaminates diesel fuel will damage all metallic components it comes into contact with. It will not, as is sometimes reported, flash into steam and shatter injector nozzles of running engines. Steam cannot exist at the pressures inside a diesel engine fuel system; however, water in its own right, because of its lack of lubricity and its corrosive influence, is particularly damaging to high-pressure, fine-tolerance components such as injection pumps and injectors.

Inorganic pollutants are, because of their incipient and gradual accumulation, more difficult to prevent than biological contaminants. That's why purchasing quality fuel from a reputable retailer is a good strategy for boats that don't go far from their homeport; for vessels operating in far-flung parts of the globe, though, such strategy is impractical. In those cases, sampling and pre-filtering and polishing (see *Professional BoatBuilder* No. 112 for more on fuel polishing systems) may be the only defense.

Installing a stripper tube—a pickup tube that extends closer to the bottom of the tank than the engine's pickup—makes water removal relatively easy. If you're designing a fuel tank, you could further specify that the stripper tube's lower opening reside within a small sump for water and other debris that settle out of the fuel column in the bottom of the tank.

A stripper tube can be connected to a small hand-operated siphon pump, or a dedicated electric pump intended for the diesel fuel. Occasional pumping will allow water to be extracted before it becomes a haven for biological life, as well as removing debris and other contaminants.

When faced with a fuel contamination problem on a customer's vessel, you need to determine just what contaminant you're confronting;

that knowledge will dictate the best method of correction. The first sign will probably be clogged filters, whether they affect the engine's running characteristics or not. Filters are windows on the dark world inside the fuel tanks. Filter bowls that are filled with water are sending an obvious signal: pump the water out of the tank. Filters that are clogged with thick, black ooze indicate a tank that needs to be opened up and cleaned.

To perform an effective cleaning, every baffled chamber within the tank must be accessed through an inspection port or ports. If the tank is not equipped with inspection ports, or if it's not equipped with enough of them, then new ones will have to be installed to fully deal with the problem. Cleaning a tank through a single inspection port in one of several baffled chambers, or through a fill or gauge port, is ineffective at best. It simply won't work, regardless of the number and type of wand and spray-nozzle attachments employed. Asphalt, bio-mats, and other accumulated tank debris are best removed by scraping and scooping with everything from paint scrapers and lintless swabs, to shovels and pressurized hot water.

Once your arms are deep in the murk of a filthy diesel tank, the effect that the fuel's accumulated microscopic elements can have on the macro components of the fuel system becomes *very* evident indeed.

Regular fuel testing, filter maintenance, and polishing can help prevent contamination. But only thoughtful system design and installation can ease the inevitable need to clean the tanks and fuel system that are exposed to all the disparate elements, contaminants, and unknowns in every gallon of fuel consumed.

Fuel tank inspection ports are essential for monitoring diesel quality and condition. There must be one port in each baffled chamber of a connected fuel tank to allow thorough cleaning after contamination with bad fuel or bacteria.

Diesel engines have changed a great deal in the past decade, and so has the fuel. The more you understand its characteristics and weaknesses, the better prepared you'll be to identify and resolve fuel-related problems as they arise.

Or maybe even before. PBB

About the Author: *A former full-service yard manager and longtime technical writer, the author now works with boat builders, owners, and others in the industry as "Steve D'Antonio Marine Consulting Inc." His book on marine systems will be published by McGraw-Hill/International Marine this fall.*