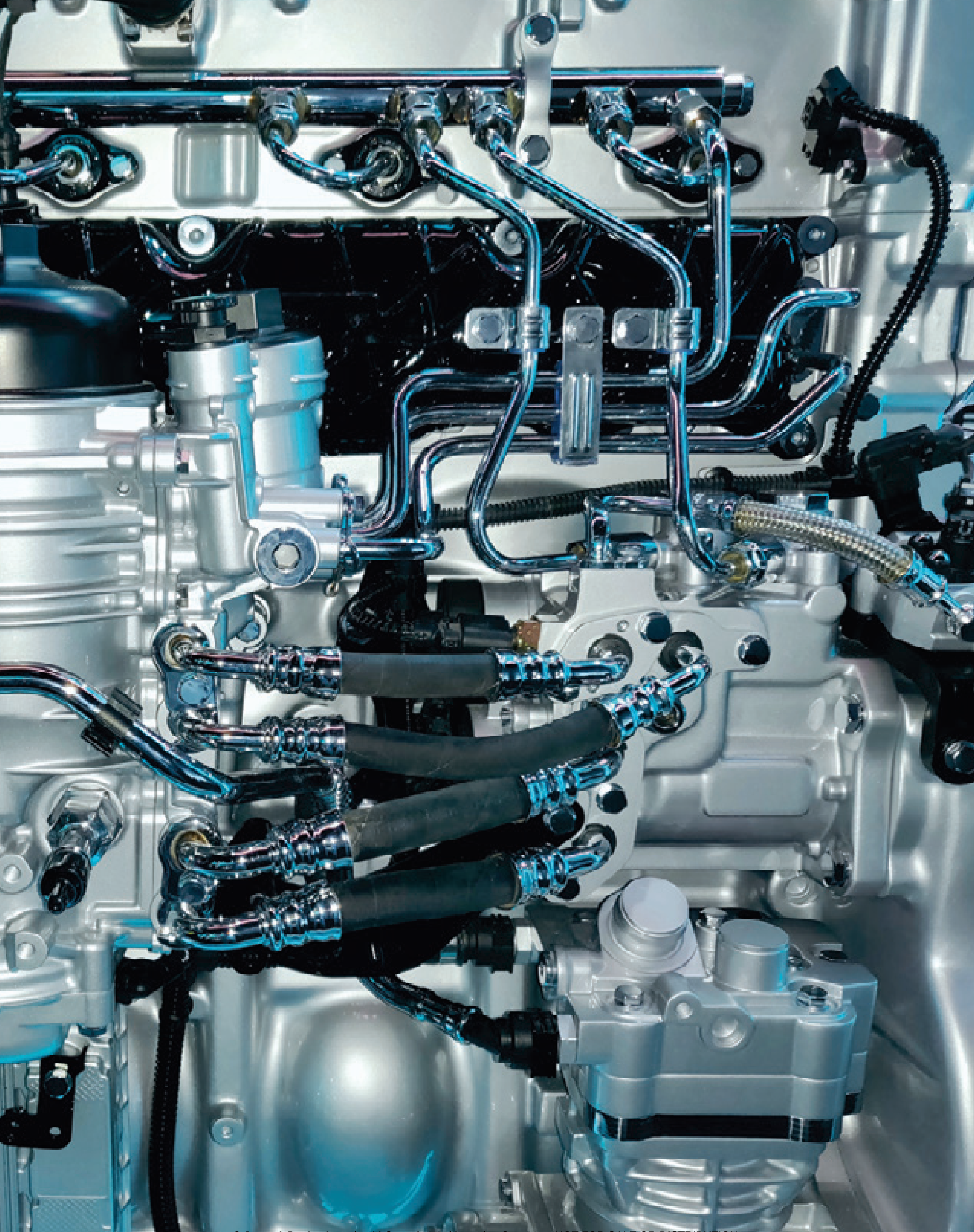

SECTION III

Diesel Fuel Systems

CHAPTER 12

Diesel Fuel Properties and Characteristics

Learning Objectives

After studying this chapter, you should be able to:

- **LO 12-1** Identify economic factors about diesel fuel that make fuel important to vehicle operations and technician service practices.
- **LO 12-2** Describe the development of standards and specifications for diesel fuel.
- **LO 12-3** Identify and explain the production methods used to produce diesel fuels.
- **LO 12-4** Identify and describe the performance requirements and properties for ASTM-quality diesel fuel.
- **LO 12-5** Identify and describe ASTM grades and applications used to select petroleum and biological-based fuels according to operating conditions.
- **LO 12-6** Describe and explain the purpose, functions, and characteristics of diesel fuel additives.
- **LO 12-7** Recommend service and maintenance practices related to analyzing fuel quality.

You Are the Technician

Over the years that you have serviced diesel engines, you have accumulated experience working with a variety of fuel quality problems. Many customers and drivers seek you out for advice about the purchase of fuel and fuel additives. Because your repair shop is located in a region of the country that experiences large swings in seasonal temperatures, you can anticipate a number of fuel-related problems in colder temperatures. Some of the problems you have encountered include:

- Drivers entering the region when temperatures are cold with fuel purchased in warmer regions
- Performance-related problems such as low power and hard starting while using fuel purchased locally in the winter
- Drivers unnecessarily using fuel additives and using them incorrectly
- Stale fuel, moisture-laden fuel, and fuel contaminated with microorganisms
- The use of biodiesel purchased in regions where biodiesel is inexpensive and widely available
- Water and asphaltene contamination
- Restricted fuel filters and fuel lines when temperatures are very low

1. For each of these situations, outline the advice you would provide to a customer, explaining the potential fuel-related operating complaints a driver could report and the cause of each of the complaints.
2. Outline the procedures you would follow to evaluate the fuel quality used by an engine you suspect has a fuel quality-related problem. Explain your reasons for using each of those procedures.
3. Make a list of service recommendations to help drivers and owners avoid fuel quality-related problems with diesel engines.

Diesel Fuel Economics

LO 12-1 Identify economic factors about diesel fuel that make fuel important to vehicle operations and technician service practices.

Diesel-powered trucks, buses, and equipment use a lot of fuel. Although diesel engines represent only 5% of the total number of registered vehicles, they consume a disproportionate amount of fuel at close to 23%. Backing up the claim that fuel is one of the largest operating expenses for commercial vehicles traveling long distance, the U.S. Federal Highway Administration (FHWA) 2018 statistics note that Class 8 trucks consume an average of 9450 gallons (gal; 35,772 liters [L]) of fuel per year (**TABLE 12-1**). Commercial vehicles, traveling long distances and hauling heavy loads, are not the largest consumer of diesel fuel. Transit buses, operating in dense urban centers, consume approximately 3.5 gal (13.25 L) per mile, which translates into a reported consumption of 9893 gal (37,449 L) of diesel fuel burned per year. Refuse trucks closely follow, traveling an average of 25,000 miles (40,234 kilometer [km]) per year and burning 8700 gal (32,933 L) of diesel fuel, according to FHWA statistics (**FIGURE 12-1**). Naturally, the routes traveled, weight or number of passengers carried, engine size, and type of service offered by diesel-powered equipment will change these reported averages. For example, major differences in fuel consumption are observed between geographic regions within North America and Europe. Class 8 vehicles registered in Canada travel an average of 91,000 miles per year (146,450 km) compared to the U.S. average of 68,185 miles per year (109,733 km).

TABLE 12-1 Average Measures of Fuel Economy and Fuel Consumption in 2018 According to Various U.S. Government Department Estimates

Class or Type	US-MPG	L/100 km	Average Yearly Consumption (Federal Highway Administration Estimates)
Class 8	5.7–7.0	41.27–33.6	
Long haul	6.7	35.11	9450
Medium-duty truck	9.6	24.5	
Delivery vehicle	8.6–11.0	27.35–21.38	
Transit bus New York	2.5	94.09	
Transit bus other	3.5–4.6	67.2–51.93	9893
Heavy-duty highway coach	7.8	30.16	

Estimates of fuel economy and consumption help explain why diesel engines are sensitive to fuel properties and characteristics. Fuel consumption not only exerts an enormous economic influence on vehicle and equipment operations but also has a major impact on engine performance. The operational requirements of the fuel supply system are further reflected in the design and construction of the fuel system. For example, fuel systems need large, onboard storage tanks, and a unique, low-pressure transfer system is required to properly clean, condition, and supply fuel to the high-pressure injection system. In fact, the largest single construction cost of a diesel engine is its fuel system. Standardized specifications for diesel fuel are established by engineering and regulatory agencies to ensure that this vital element of engine operation is dependable. Because of the importance of fuel to performance and vehicle operation, it is essential for technicians to have a thorough understanding of diesel fuel properties and characteristics to correctly recommend and select appropriate fuel grades and fuel additives for the wide variety of diesel engine applications. Operating conditions; temperatures; location of engine operation; and whether the vehicle is stationary, marine, or used for on- or off-highway applications all significantly change recommendations for the correct selection of fuel and choice of additives. A competent diesel technician should have the expertise to make recommendations about the use of different grades of diesel fuel and fuel additives.

Environmental considerations and legislative requirements for renewable fuels are adding complexity to today's fuel characteristics. This complexity can potentially lead to an incorrect selection of fuel that can have dramatic, negative effects on engine durability and reliability. Diesel technicians should also be familiar with identifying performance problems and engine failures associated with fuel quality as well as the effect of fuel additives on treated fuel. To help the technician understand the function and purpose of diesel fuel properties and characteristics, this chapter presents relevant and practical information about diesel fuel production, specifications, and performance standards. Information regarding fuel handling, fuel additives, and the problems associated with fuel quality are included to enhance technician understanding of fuels as they are related to service and maintenance practices associated with diesel engines.

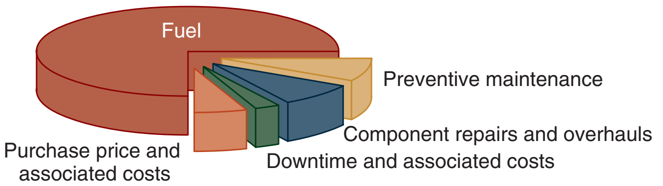

FIGURE 12-1 The cost of fuel is the largest portion of the life cycle vehicle cost for most heavy-duty commercial vehicles.

Development of Diesel Fuel Standards

LO 12-2 Describe the development of standards and specifications for diesel fuel.

Diesel fuel properties and characteristics are matters that a technician can change to some extent, but it is even more important to understand the effects of fuel quality on engine operation. This information is especially relevant when identifying the effects that abnormal or deteriorated fuel conditions can have when investigating the causes of engine or component failure or when diagnosing performance-related complaints.

While the term *diesel fuel* bears the name of the engine's inventor, it is a generic term that refers to a range of fuels burned in compression ignition (CI) engines. Each grade has its own unique designation and properties. Some diesel fuel products are made from petroleum while others are processed from biological sources and even waste products. The following section surveys the development of diesel fuel since the invention of the diesel engine to explain production methods and the reasons for adopting current diesel fuel standards.

Early Fuels

Coal dust was the original diesel engine fuel. Rudolf Diesel's prototype engine, based on his 1892 patent for a CI engine, used this resource, which was found in plentiful quantities around the mines and factories of Germany's industrialized Ruhr Valley. The fuel did not work well, and Diesel searched for an alternative, liquid fuel. In 1900, a demonstration of an early prototype engine took place at the Paris World Exhibition in France. The first biodiesel fuel made of peanut oil fueled this engine, and this fuel was chosen in part due to the encouragement of the French government. To support its colonies around the world, the development of a renewable, nonpetroleum-based fuel was an initiative that enabled small industry, farmers, and other producers to effectively compete with the monopolized oil industry of the time. Until the 1920s, biologically derived fuels, or biodiesel, powered many diesel and other CI engines. Biodiesel refers to diesel fuel derived from biological sources such as vegetable oils or animal fats. In contrast, petroleum diesel is refined from crude petroleum oil. Crude petroleum oil is considered a mineral oil because it is extracted from the earth.

ASTM Diesel Fuel Standard

For a number of reasons, fuels derived from petroleum are the more favored alternative to biologically based diesel engine fuels. **Petroleum distillates** are fuels recovered from distilling crude oil that can readily burn in the diesel engine and historically have been widely available because there was plenty of this byproduct left over after refining gasoline for automobiles. These are the same fuels commonly used for lanterns and for heating homes (kerosene and other light hydrocarbons), and they can be used to operate diesel engines (**FIGURE 12-2**). Until the 1930s, these petroleum products varied widely in composition and quality, so their performance was unpredictable. An engine sold to an operator in Texas would not perform the same way as an engine in Edmonton, Canada, or London, England, because the composition of fuel varied according to the qualities of the base oil used to refine gasoline. Manufacturers began to develop diesel fuel specifications after observing numerous fuel and engine failures caused by fuel composition. They also wanted to guarantee customers a consistent engine power output and offer warranties. None of this was possible until an industry standard, outlining what should be left out of fuel and what should be left in, provided diesel fuel with consistent properties and characteristics. Today, **ASTM International** (formerly known as the American Society for Testing Materials) establishes diesel fuel standards. While most countries possess their own separate and distinct performance standards for diesel fuel, the ASTM-defined fuel standards are widely recognized around the world. Petroleum diesel fuel is defined in ASTM standard D975, and biodiesel specifications are set in ASTM standard D6751. ASTM diesel fuel grades are designated as 1-D (for Diesel #1) and 2-D (for Diesel #2); 1-D and 2-D are both commonly used

FIGURE 12-2 Kerosene, commonly used as home heating oil and in older, off-road and farming equipment, is a low sulfur content fuel similar to 1-D grade diesel fuel.

by on- and off-road diesel engines. In North America, 2-D is commercially retailed at pumps, but 1-D and 2-D are both available at pumps outside of North America (**FIGURE 12-3**). ASTM grade 4-D is used primarily for home heating oil, but it is also used by some large-displacement, stationary, low-speed diesel engines in applications that predominantly involve constant speed and load, such as ship or locomotive engines, large water pumps, and power generators. Because 4-D is not as refined as carefully as 1-D and 2-D, it has impurities and other characteristics that will quickly damage on-highway engines and should never be used in them. There is no ASTM 3-D designation.

▶ TECHNICIAN TIP

Beware of performance claims made by additive suppliers. In the United States, the ASTM International and, to some extent, the Environmental Protection Agency (EPA) regulate diesel fuel properties. While most characteristics of diesel fuel are ASTM defined, the EPA imposes additional environmental standards to minimize the formation of toxic emissions when fuel burns. The EPA also evaluates fuel additives for potential toxicity but does not make any endorsement of performance specification.

FIGURE 12-3 The two common ASTM diesel fuel grades for on-highway use are 1-D and 2-D.

Types of Diesel Fuel and Production Methods

LO 12-3 Identify and explain the production methods used to produce diesel fuels.

Fuels, such as diesel or gasoline, are derived from crude petroleum oil. Crude oil is a mixture of various types of hydrocarbon molecules linked together into chains. Because the chains are composed mostly of hydrogen and carbon, the name *hydrocarbon* is given to fuels containing these elements (**FIGURE 12-4**). Some hydrocarbon fuel chains are small and arranged with different ratios of hydrogen to carbon. Fuels that have higher ratios of hydrogen to carbon, such as propane and natural gas (more correctly called *methane*), are lighter. Other chains are heavier and have greater carbon-to-hydrogen ratios. High-carbon, low-hydrogen molecules are typically linked together into larger chains that form heavier, liquid molecules such as diesel fuel. Tar, engine oils, and asphalt liquid are made from the heaviest, high-carbon, low-hydrogen chains of hydrocarbons. By boiling the oil in a pressurized vessel and collecting oil vapors through a process known as **distillation** or thermal cracking, hydrocarbon chains are separated into **fractions**, or cuts, with different hydrogen-to-carbon ratios. Separation of fuel molecules during distillation occurs according to the boiling point temperature of each fraction. Smaller, lighter hydrocarbon molecules have a lower boiling point and larger, heavier molecules have a higher boiling point. The boiling and vapor separation process produces petroleum products ranging from propane and butane (also called *light ends* or *light fractions*) to gasoline and other **middle distillates**, which includes diesel fuel (**FIGURE 12-5**). Catalytic cracking of heavy hydrocarbons can take place at lower temperatures and pressures than thermal cracking. Heat, slight pressure, and a catalyst material are used to break apart long, heavy hydrocarbon chains while using less energy.

Diesel Fuel Specifications

Although diesel and gasoline fuels are both hydrocarbons, they are different from one another. Diesel fuels contain heavier, longer hydrocarbon chains, which have a higher boiling point than gasoline and a higher carbon-to-hydrogen ratio. Kerosene, home heating, and jet fuel account for another portion of middle-distillate production. These fuels have specifications and physical properties similar to diesel fuel. However, while sharing similar properties, they must be used only for their specific applications. Fuel specifications and production processes, developed to operate a camp stove, fly an aircraft, and power an on-highway engine are different from one another and are not interchangeable. For example, kerosene, used as furnace oil, typically has more wax content and impurities and has fewer additives than other fuels. However, kerosene that is used to operate a jet turbine engine needs to resist gelling at low temperatures encountered at high altitudes. Any water dissolved in the fuel must not freeze, so anti-icing agents are added to jet aviation (Jet-A) kerosene fuel. On-highway diesel engines could use either fuel for a short time, but using kerosene furnace oil

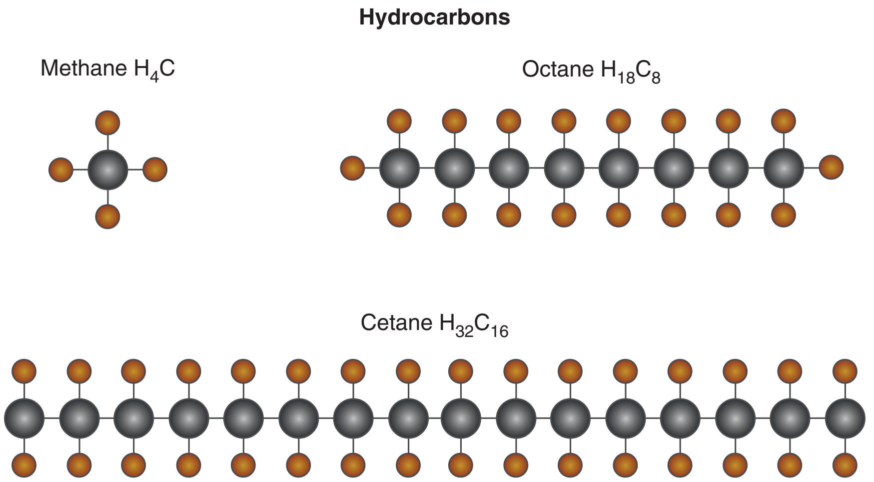

FIGURE 12-4 Fuels have different ratios of carbon and hydrogen. The number of atoms in a fuel molecule and the type of chemical bonds it has determine a fuel's properties.

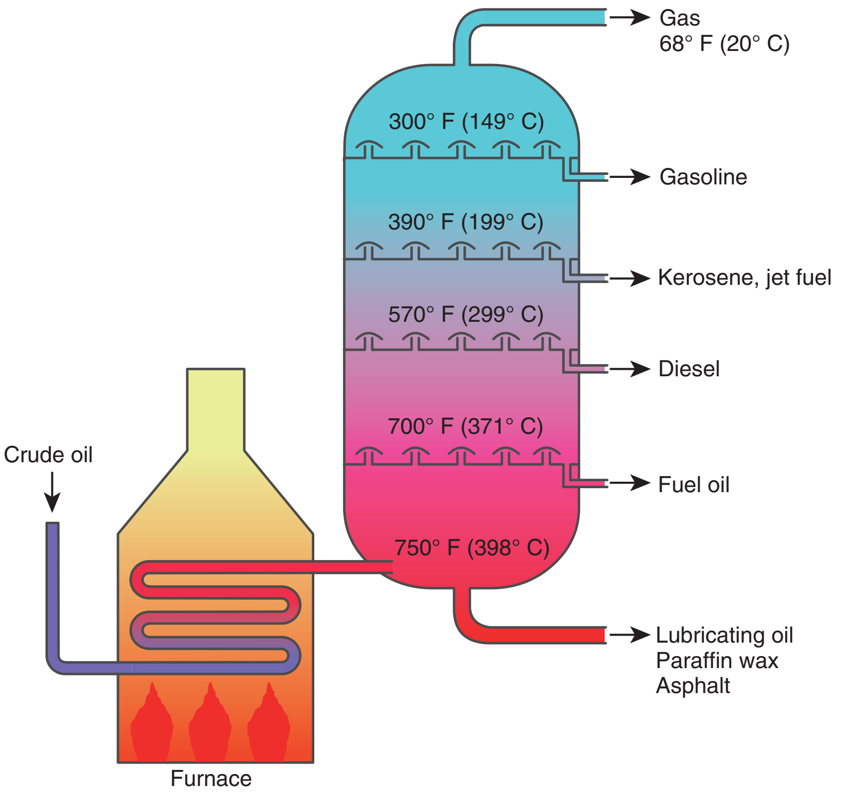

FIGURE 12-5 Oil is heated and the vapors condensed to distill various types, or fractions, of fuel. Diesel fuel is a heavier fraction than gasoline and is similar to heating and jet fuel.

quickly destroys many precision injection systems used in the latest engines that run with close operating tolerances. The lack of good lubricating properties in Jet-A, a fuel that powers turbine engines, means that diesel engine injection systems can be rapidly worn out by its use.

Jet Propellant-8 Fuel

To underline the closeness of middle distillate fuel properties, it is interesting to note fuel specifications for military use. A great deal of logistical complexity is required to supply several different types of fuel, such as gasoline and diesel fuel for ground equipment and aviation fuel for aircraft. To address this problem, the United States, British, NATO, and other militaries around the world have adopted a single fuel to power all its equipment and machinery called *jet propellant-8 (JP-8) fuel*. Since 1990, JP-8 has been used for fueling aircraft, heaters, stoves, electrical generators, ground and other diesel-powered tactical equipment, such as tanks and personal carriers, Humvees, and even motorcycles. JP-8 is lighter than 2-D and is similar in properties to kerosene and a commercial aircraft fuel grade such as Jet-A. To improve its performance in all types of engines and fuel systems, corrosion inhibitors, anti-icing additives, and lubricity improvers are added to JP-8. To make it safer to handle, antistatic agents are added to prevent electric charges from building up when it is transferred between fuel tanks. JP-8 also has a higher flash point than diesel fuel, which means it doesn't ignite as easily when the fuel comes in contact with open flames or sparks. The fuel has a density that ranges from 6.47–7.01 lb/gal (0.78–0.84 kg/L) when measured with a hydrometer.

Synthetic Diesel Fuel

Diesel fuel is also produced by liquefying hydrocarbon gases, such as methane, and modifying the chemical structure of the hydrocarbon molecules to produce a liquid at room temperature. Such **gas-to-liquid (GTL) fuels** are manufactured by using a chemical process invented in Germany during the 1920s called the **Fischer-Tropsch reaction**. Coal, carbon monoxide (CO), and gases produced by decomposing wood and other plant material are used to manufacture **synthetic diesel fuel** (diesel fuel that is not derived from petroleum) using this process.

Pyrolysis-Derived Fuels

Pyrolysis is another method of fuel production that can use any hydrogen-carbon material. The pyrolysis process uses a wide variety of feedstock that ranges from grass, agricultural waste, wood chips, old vinyl records (that were used on turntables), or even garbage redirected from landfills. These materials are ground up, dried, and then placed into a vacuum chamber where they are heated to a temperature hot enough to vaporize the material. In the absence of oxygen, the material does not combust. Instead, the materials are vaporized by the heat, and then vapors (actually smoke) are collected and condensed into liquid fuel. Given the steps used to make pyrolytically derived fuels, it is easier to describe them as liquid smoke (**FIGURE 12-6**). Testing of fuels manufactured from this process has successfully demonstrated their viability. Low-quality pyrolysis liquids are currently used to heat industrial buildings. However, the maintenance costs associated with its use, plus volatile oil prices, have discouraged more commercial production of this fuel.

FIGURE 12-6 This jar of fuel capable of burning in modified diesel and jet turbine engines contains liquid smoke derived from pyrolysis of wood chips.

FIGURE 12-7 This fender decal indicates the maximum limit of biologically derived fuel that the engine can tolerate. If biodiesel contaminates lubricating system oil, it chemically changes the engine oil, which leads to catastrophic engine failures.

▶ TECHNICIAN TIP

What do the numbers after the letter B for biofuel indicate? Biodiesel is fuel made exclusively from biological sources, such as plant oil or animal fat, or a combination of petroleum-based fuel and biological fuel sources. The number following the letter B indicates the percentage of biologically sourced fuel combined with petroleum fuel. This means biodiesel made from 20% biological fuel sources and 80% petroleum would be designated B20. The oil filler cap of an engine capable of running on biodiesel will typically display the maximum limit of biologically derived fuel that it can tolerate (**FIGURE 12-7**).

Diesel Fuel Price and Production Capacity

Historically, the production and retail cost of diesel fuel has been cheaper than gasoline because it is a byproduct of gasoline production. However, seasonal variations in climate can drive fluctuations in the retail price of diesel fuel. In winter months, demand for home heating fuel increases, which reduces the worldwide supply of diesel fuel. Reduced supply applies an upward pressure on the cost of diesel fuel.

In Europe, diesel fuel is still typically cheaper than gasoline because most countries have favorable taxation policies to encourage the use of more fuel-efficient diesel engines. Since 2004, the price differential between gasoline and diesel has moved in the opposite direction in the United States (**FIGURE 12-8**). The introduction of **ultra-low–sulfur diesel (ULSD)** in 2006 was the justification for a slight increase in production costs at that time. Today, the cost of refining diesel fuel is lower than it was in 2012 due to improvements in refining methods, such as the expanded use of catalytic cracking. Globalpetrolprice.com, a business analytics firm respected for accurately and reliably monitoring fuel prices around the world, has examined this trend. Its 2019 data set of 161 countries reports that 84% of those countries surveyed have more expensive gasoline than diesel fuel. On average, in those countries, diesel fuel is 9.84% cheaper. In the United States, the price of diesel at the fuel pump has increased by close to 24% between 2012 and 2019 while the price of gasoline has dropped by approximately the same amount. But taxes on both gas and diesel fuel account for a different percentage of the retail fuel price; gasoline is 18.4 cents per gallon and diesel fuel is 24.4 cents per gallon. The largest increase is observed in the marketing and distribution costs reported by petroleum companies. These costs, priced into the retail value of diesel at the pump, have more than doubled. A number of industry analysts prefer to explain the increase by using the simple economic principle of supply and demand. During periods of economic expansion and growth, more people and goods are transported. This means buses used for public transportation, delivery trucks, line haul tractors, off-road machines, construction equipment, and power generators

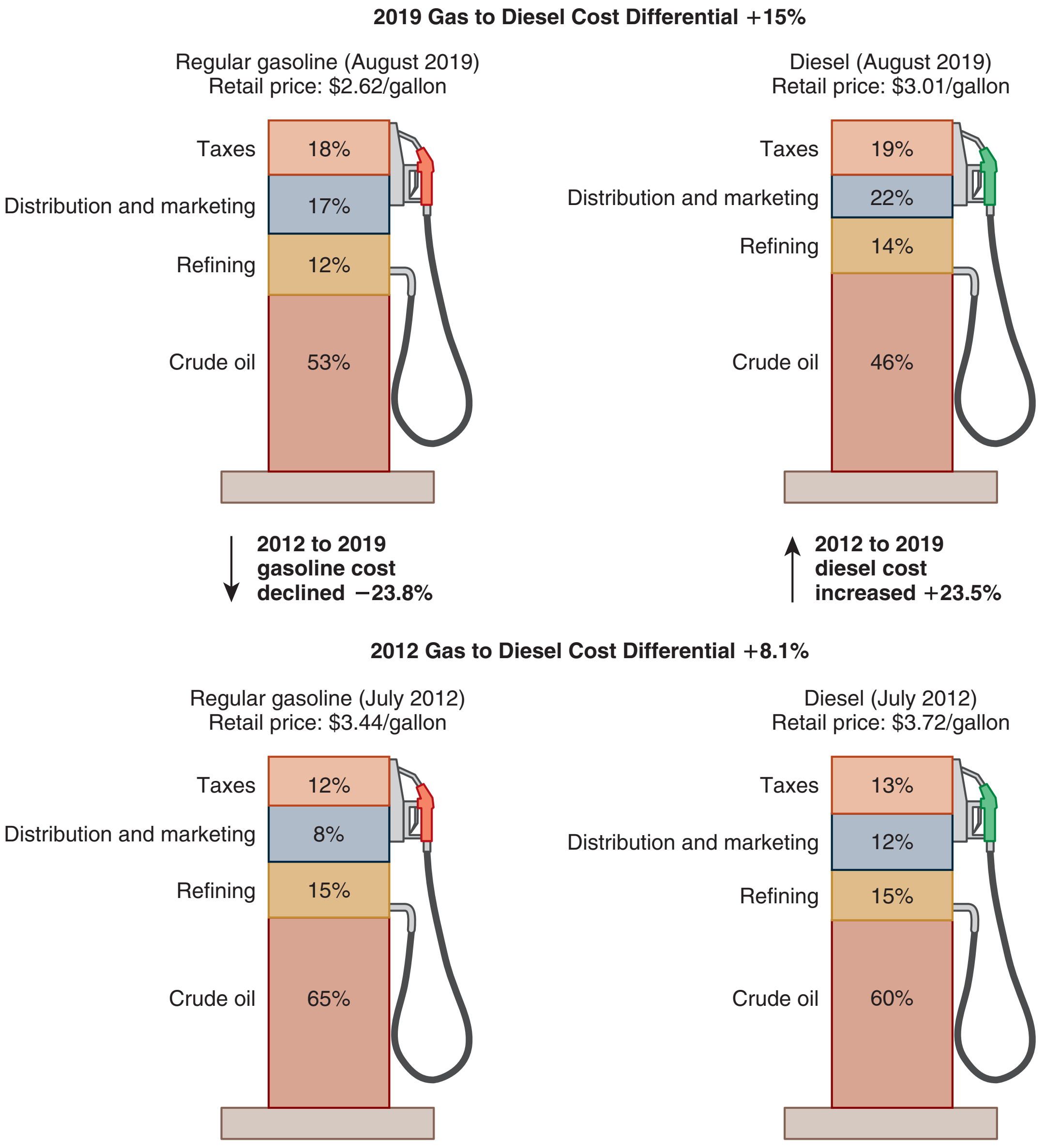

FIGURE 12-8 The lack of capacity of refineries in North America to produce diesel fuel has driven up the cost, primarily in the United States, in recent years.

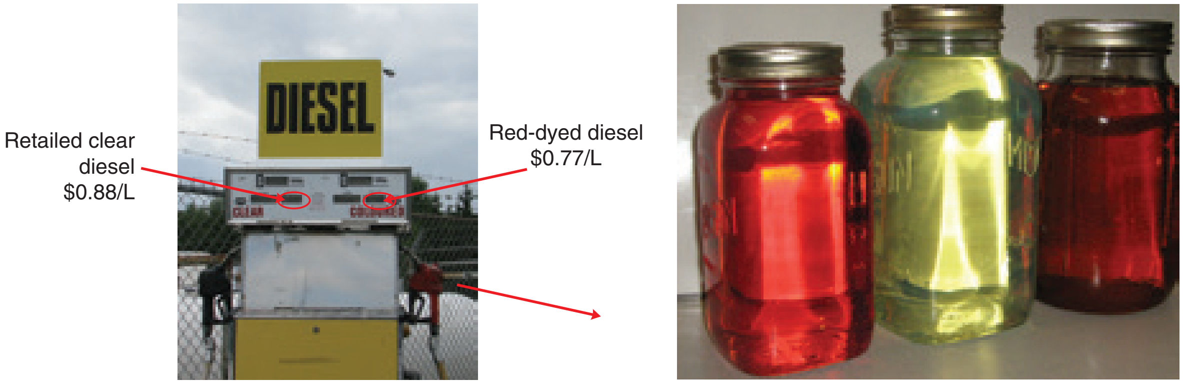

FIGURE 12-9 Fresh, clean, petroleum-based diesel fuel is clear when commercially retailed in North America. Dyed fuels are intended for specific uses and taxation categories.

consume more diesel fuel. Dependence upon diesel engines has translated into increased demand for diesel fuel, which significantly decreases the available supply. The result is the increased retail price of diesel fuel compared to gasoline. Unfortunately, in the USA, fuel refinery capacity has not kept up with the demand for diesel fuel, causing the supply to decrease over the past decade. With no plans for the construction of new refineries, this trend in the United States is not expected to reverse anytime soon.

Fuel Color

Good-quality, fresh commercial vehicle grade diesel fuel is normally clear to light amber in color depending on the refining process and the source of the oil used to produce it (**FIGURE 12-9**). Certain diesel fuels are dyed to differentiate their sources and applications. Aviation fuel, for example, is dyed blue. Diesel fuels intended for home heating oil and agricultural machinery are dyed red because they are taxed at a lower rate and are not permitted for use in on-highway vehicles. The dyes have no effect on fuel performance or emissions.

Diesel fuel may darken after prolonged storage due to oxidation. Oxidation takes place when fuel molecules combine with atmospheric oxygen. This darkening is often accompanied by performance problems due to a change in the ignition quality of the fuel. Low engine power, accompanied by high exhaust temperatures, excessive fuel consumption, and high turbocharger boost pressures from fixed geometry turbochargers, are all symptoms of stale fuel. Poor-quality, low-cetane fuel produces identical performance-related symptoms. If fuel darkening is accompanied by the formation of sediment, the fuel can foul and plug fuel filters (**FIGURE 12-10**). Diesel fuel can also absorb water, which causes fuel to become cloudy and develop a gray color if it is fresh. Old, stale diesel fuel that has absorbed water will turn dark brown.

> **▶ TECHNICIAN TIP**
>
> When evaluating diesel fuel quality, in addition to color and the American Petroleum Institute rating, the fuel's odor is another indicator of its quality. Fresh fuel has a strong, pungent, characteristic odor. Old or stale fuel lacks a strong odor when exposed to air and smells like varnish or turpentine.

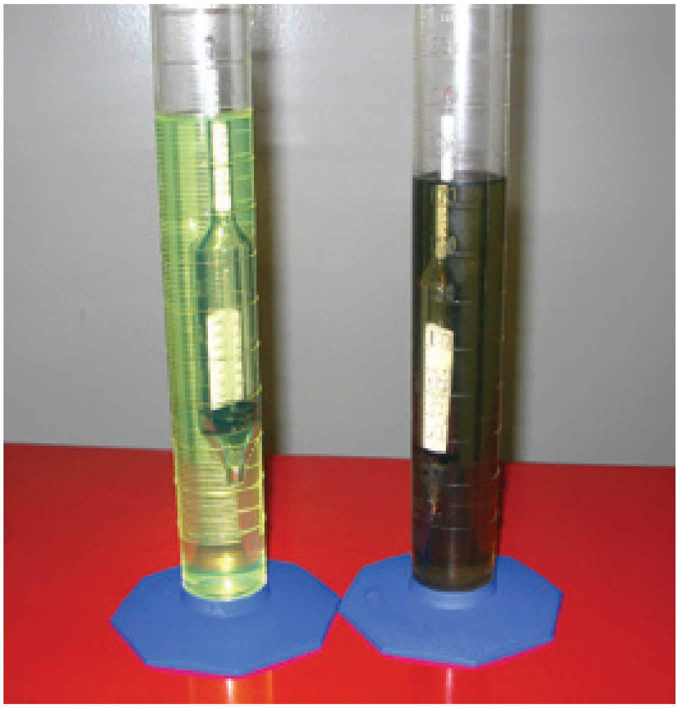

FIGURE 12-10 Older fuel darkens and becomes cloudy as it absorbs water. It will also develop a varnish or turpentine-like odor.

Sulfur and Diesel Fuel

Sulfur is naturally present in crude oil that is pumped from underground deposits (biodiesel has no sulfur content). Sulfur that is not removed during the refining process becomes a problem when the fuel burns. The sulfur content of diesel fuel increases the production of particulate matter (PM) emissions because some of the sulfur in the fuel is converted to sulfate particles in the exhaust. How much sulfur is converted to PM varies from one engine to another but reducing sulfur content in fuel decreases PM in almost all engines. For this reason, the EPA began to limit the sulfur content of on-road diesel fuel in 1993 to 0.05% mass or 500 parts per million (ppm) maximum, when it mandated the production of **low-sulfur diesel (LSD)** fuel.

Reducing sulfur content of fuel can increase engine longevity. Sulfur can be deposited on rings, which causes premature wear and sticking. Injectors can have sulfur buildup in spray holes that can interfere with proper injector operation and fuel distribution. Sulfur can also combine with water, resulting in the production of corrosive compounds that damage bearings and other metal parts. Acidic sulfuric acid in fuel will cause damage to fuel injectors and contaminate engine oil. Lower sulfur content in the exhaust stream also translates into less corrosion of the exhaust system.

Ultra-Low–Sulfur Diesel

The sulfur content of ultra-low–sulfur diesel (ULSD) is reduced from approximately 500 ppm to 15 ppm. This cleaner diesel fuel, designated S15, which is appended to the fuel grade (e.g., 1-D S15), became available beginning in 2006. One year later, diesel exhaust aftertreatment systems were introduced to meet the EPA 2007 emissions standards (**FIGURE 12-11**). Emissions reduction in heavy-duty (HD) diesel trucks and buses requires the use of exhaust aftertreatment devices, such as diesel particulate filters (DPFs), NOx adsorber catalysts (NACs), liquid selective catalytic reduction (SCR) catalysts, and diesel oxidation catalysts (DOCs). ULSD is necessary to avoid damaging or "poisoning" the catalytic materials in these devices with sulfur. There are other consequences of using diesel fuel that has reduced sulfur content (**TABLE 12-2**). In Europe, ULSD fuel was introduced much earlier, with some countries adopting the 15 ppm limit in the early 1990s. The method used to remove sulfur content from fuels unfortunately led to a reduction of the lubricating properties of fuels prior to 2006. Large fat- and wax-like molecules that normally gave diesel fuel good lubricating properties were often removed at the same time as the sulfur. These same molecules also made certain elastomer-type seals in the fuel system "plumper," which helped them to perform sealing functions. Consequentially, sulfur removal from LSD fuels was traced to many fuel injection pump failures and leaks.

FIGURE 12-11 ULSD fuel is required for all 2007 and later diesel engines equipped with diesel particulate filters. The label on this fuel tank indicates that ULSD is required.

TABLE 12-2 Benefits of Using Sulfur-Reduced Fuel

Diesel Fuel Type	Sulfur Limit	U.S. EPA Year of Mandate
On-highway	500 ppm 30 ppm 15 ppm 2500+ ppm	1993 2004 Mid-2006 Pre-1993
Off-road	500 ppm 15 ppm	Mid-2007 Mid-2010
Railway and marine	15 ppm	Mid-2012

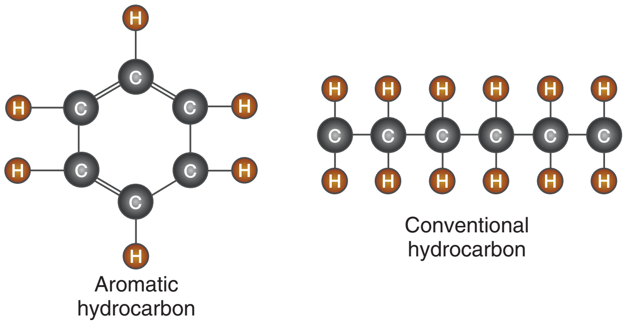

FIGURE 12-12 Aromatic compounds are difficult to burn. Unburned aromatic molecules give diesel exhaust its distinct odor.

Aromatic Content

Aromatic content refers to a particular type of hydrocarbon molecule that contains sulfur and nitrogen. Because of the bonds formed between these elements and hydrocarbon chains, aromatic fuel molecules are large, complex, and difficult to burn. The characteristic odor of unburned aromatic fuel in diesel exhaust is the result of the aromatic content of diesel fuel. Because aromatic fuel molecules are hard to break apart and burn, their presence in fuel contributes to the increase of emissions (**FIGURE 12-12**). Current environmental legislation limits aromatic content to 15% by volume, with some jurisdictions opting for 10%. California has limited aromatic content to 10% since 1993, with a 20% exemption for small refineries. ASTM standards limit aromatic content to a maximum of 35%.

▶ TECHNICIAN TIP

Hydrotreating fuel, which is a chemical process used by refineries to remove sulfur, simultaneously reduces its aromatic content. Fuels with lower aromatic content may cause fuel system leaks if fuel system seals and gaskets have been previously operated with high aromatic fuels and absorbed their content. Fuels with high aromatic content have molecules that may be absorbed by some fuel system seals and O-rings. The use of low aromatic fuels may cause some seals and O-rings to lose these molecules and shrink, which causes fuel system leaks. B-100 biodiesel has no aromatic content, but fat- and wax-like molecules in biodiesel prevent seal deterioration and increase fuel lubricity.

Performance Requirements for Diesel Fuel

LO 12-4 Identify and describe the performance requirements and properties for ASTM-quality diesel fuel.

The operation of diesel engines demands that certain performance requirements be met by fuel:

1. **Starting ease:** Diesel fuel needs to ignite at low temperatures and pressures found in the combustion chamber during cranking. If not, immediately after the engine starts, a relatively cool combustion chamber can extinguish combustion flames. Fuel quenching causes small fuel droplets to be left unburned and forms white smoke. Diesel fuel should have properties that promote fast ignition and complete combustion at low pressures and temperatures.
2. **Lubricating properties:** The lubricating properties of fuel must aid in the reduction of engine and fuel system wear. For example, high-pressure injection systems have moving parts that operate with very small clearances, which are lubricated only by diesel fuel. The lubricating properties of diesel fuel should minimize wear in these sensitive areas (see the *Lubricity* section of the chapter).
3. **Efficient production of power:** Engines must extract the maximum amount of energy from the combustion process. Diesel fuel requires sufficient heat content to produce power ratings published by the manufacturer. Waxes and other heavy hydrocarbon compounds, with a large number of molecular bonds, generate the greatest heat release from diesel fuel when they are broken.
4. **Satisfactory operation during low-temperature conditions:** Diesel fuels contain wax-like molecules that solidify at low temperatures. Gelled fuel will foul or plug filters and fuel lines and prevent fuel from reaching the engine. To minimize this problem, diesel fuel refineries blend fuels and additives together to suit local climate or seasonal conditions where engines are operated.
5. **Low noise production:** Prolonged ignition delay time leads to increased combustion noise from the diesel engine. Diesel fuel properties can affect noise by increasing or decreasing ignition delay time.
6. **Long filter life:** Diesel fuel should be free of particles that cause abrasive wear of the fuel system. Other particles that do not dissolve in fuel include gums, resins, and asphaltenes. These particles can quickly foul and plug filters.
7. **Good fuel economy:** Fuel economy and power are proportional to the heat content of diesel fuel. Increasing the density of fuel will generally increase its heat content and improve fuel economy.
8. **Low emissions:** Fuel chemistry can have an impact on engine emissions. Aromatic and sulfur content of fuel, as well as other chemical properties, can change an engine's emissions output.

The next sections will outline fuel properties and characteristics related to the performance demands made of diesel fuel.

▶ TECHNICIAN TIP

Diesel fuel contains a higher number of paraffin and other wax-like compounds than gasoline. These waxes will congeal when the fuel is cool, restricting fuel flow through lines and filters. The result is low engine power or a failure of the engine to run at all. For this reason, additives are blended into fuel by refineries according to geographic and seasonal requirements. This means fuel purchased in a cold region may not perform well if the vehicle travels to a warmer geographic location (see the *Pour Point and Cloud Point* section of the chapter).

Cetane Number

The **cetane number (CN)** is one of the most significant properties of diesel fuel. CN is a measure of the ignition quality of fuel and indicates how easily a fuel ignites in the combustion chamber. Fuel with a high CN ignites easily and burns faster compared to a fuel with a low CN. When combustion chamber pre-ignition temperatures are reduced by variables such as low compression pressure, cool ambient temperature, and cold coolant temperature, an engine requires a high CN fuel to start easily and burn fuel quickly (**FIGURE 12-13**). Fuel with a high

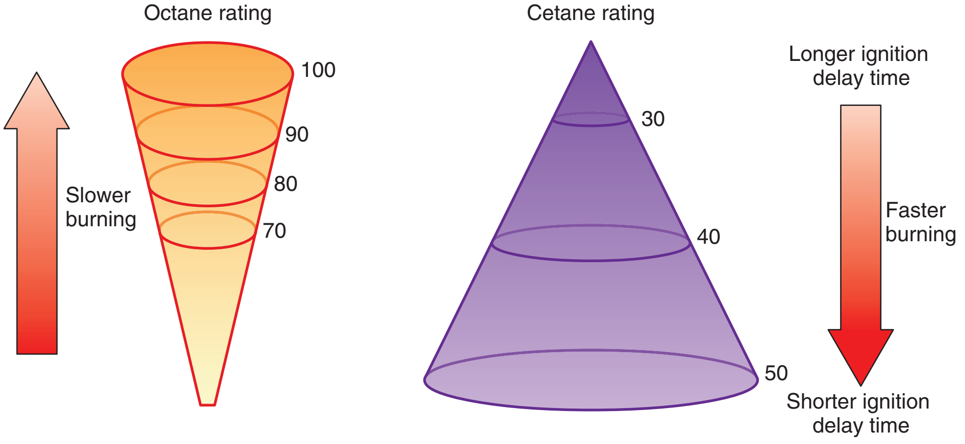

FIGURE 12-13 CN is used to measure the ignition characteristics of diesel fuel. The higher the CN, the faster the diesel fuel will ignite and burn.

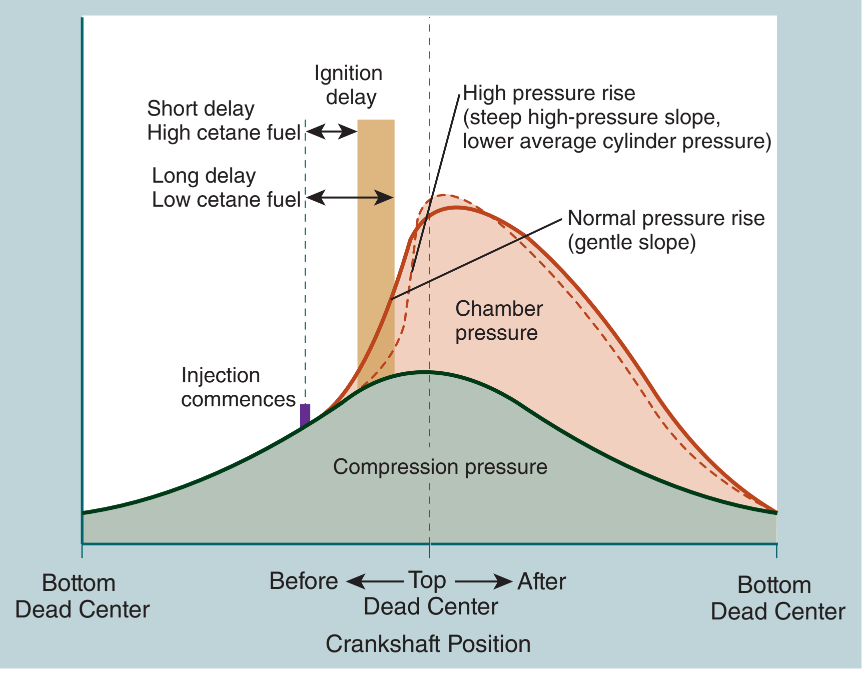

FIGURE 12-14 Fuel with a low CN will lengthen the ignition delay phase and cause an engine to be harder to start, run more roughly, and have noisier combustion.

CN will not only start an engine more quickly but also burn more quietly because the ignition delay period is shortened. A shortened ignition delay period will allow more time for fuel to burn and produce fewer emissions while providing better fuel economy.

CN can be compared to the **octane number** used to measure gasoline's ignition characteristics (**FIGURE 12-14**). Octane and cetane numbers both are measures of ignition quality, but the numbers representing the same ignition characteristics are inversely related to one another. For example, gasoline with a low octane number ignites more easily and burns more quickly when compared to high octane number gasoline. High-octane gasoline is needed in spark ignition engines that operate with high compression ratios. However, diesel fuel with a high, not low, CN is needed to ignite more quickly and burn faster, providing smoother, quieter, and cleaner engine operation.

Measuring Cetane Number

The CN of diesel fuel is traditionally calculated by comparing the sample fuel against a reference fuel with a CN of 100. This means if the fuel has a CN of 45, then the fuel will ignite and burn at speeds 45% longer than the time required for a CN 100 fuel. Ignition quality of the fuel is analyzed using a single piston engine operated on the sample fuel. The ignition delay time of the combustion event is measured and then compared with the delay time on a scale of fuels with a corresponding CN. Matching the delay time with that of another reference fuel with a known CN establishes the CN of the sample fuel.

The CN for a fuel can be chemically determined only by using specialized test equipment that measures ignition quality. A correlation between the weight or the **American Petroleum Institute (API) number** of the fuel measured with a hydrometer and cetane is not possible. Remember that CN ratings apply only to diesel and mid-distillate fuels, not to gasoline.

In North America, the ASTM established the minimum requirement for 1-D and 2-D diesel fuel as CN 40 in 2011, but most engines need a CN of 45 to run well. This means the ASTM CN is typically much higher when retailed at fuel station pumps. In fact, a recent U.S. survey of retail pump fuel quality found most fuel with a CN between 47 and 52 depending on seasonal variations. To improve air quality, California requires a minimum CN of 53 and Texas 48. Premium diesel fuel can have a CN as high as 60. In Europe, the minimum CN used for passenger automobiles is 55. For biodiesel, the ASTM standard is a minimum CN of 47.

When engines operate below 32° F (0° C), a higher CN is recommended. Engines that operate at slower speeds can use lower CN fuel because the performance of slow-speed engines is not detrimentally affected by a long ignition delay period. In fact, large, low-speed engines can operate on fuels with a CN as low as 20 while most late-model, high-speed passenger car diesel engines operate best using CN 55 fuel. Higher CN fuel results in shorter ignition delay, providing improved combustion quality, lower combustion noise, easier cold starting, faster warm-up, less white smoke, and in many engines, reduction of emissions. The type of fuel molecules in naturally high CN fuel also breaks apart more easily but tends to release less energy. This means that a naturally high-cetane fuel, such as 1-D, produces less power and potentially increases fuel consumption relative to 2-D. However, low-quality fuel with higher aromatic content that is more difficult to ignite and burn can have its CN artificially increased with cetane-boosting additives. In these cases, fuel economy and power are not reduced, and the additive can improve engine performance. Alkyl nitrates and di-tert-butyl peroxide (DTBP) are two common cetane-boosting additives used by refineries.

▶ TECHNICIAN TIP

How can a technician determine if a fuel has a low CN? Listening to the sound an engine makes, noting the smell of the exhaust, measuring fuel consumption, or examining the types of failures encountered by an engine's exhaust gas recirculation (EGR) valves are all ways to make this determination. Fuels with a higher CN have lighter, less complex molecules that are easier to ignite and burn than molecules found in low cetane fuels. That translates into a quieter, smoother-running engine. Complex and heavier fuel molecules have more molecular bonds that require higher combustion temperatures and pressure to completely burn. This means that low CN fuel may not completely burn at low engine speed and load conditions. Combustion byproducts can foul sensitive components such as EGR valves.

Cetane Index

Cetane index (CI) is a calculated value determined by measuring the density and volatility of fuel to generate a CN. The reason for using a CI is to avoid expensive CN testing by approximating what CN is expected from a fuel sample. CI calculations are performed by measuring fuel density and the temperature at which 10%, 50%, and 90% of the fuel evaporates. Simpler CI tests may only measure density and the temperature at which 50% of the fuel sample evaporates. Tests for CI are not as accurate as a measurement of CN and cannot take into account the effect of cetane-boosting additives.

▶ TECHNICIAN TIP

Cetane booster, an additive to increase the CN of fuel, is one of the few useful additives to add to some low-quality fuels. The commercially available additive will increase the naturally low CN in fuel to that of a higher CN fuel. Engines that may need to idle for extended periods, such as ambulances, fire trucks, and other emergency vehicles, can benefit from cetane boosters. An increased CN will prevent the formation of combustion deposits and reduce the production of engine slobber. Engines that have frequent EGR valve failures or face plugging of oxidation converters due to extended idle can also benefit from CN booster. Fouling and plugging of EGR valves and oxidation converters can be eliminated in many cases. It is important to note that these additives must be used sparingly. Excessive cetane booster additive in fuel will alter fuel chemistry and result in increased particulate emissions, often with heavy black smoke under load when fuel is severely overconcentrated with cetane booster.

Flash Point

The **flash point** of a fuel is defined as the temperature to which the fuel must be heated to produce enough vapor to ignite when exposed to a spark or open flame (**FIGURE 12-15**). If the flash point of a fuel is too low, the fuel is a fire hazard that is prone to accidental ignition and even explosion. Depending on the fuel grade, the flash point is 100–125° F (38–52° C) for most diesel fuels. This contrasts with gasoline, which has a flash point of at least –45° F (–43° C) or lower, to allow it to vaporize at cold temperatures and start an engine. To illustrate this difference, consider two samples of fuel: diesel and gasoline at room temperature. Hypothetically, a lit match quickly doused in diesel fuel will likely be extinguished. The same lit match doused with gasoline will likely produce an immediate fire (***do not attempt either of these experiments***). Because the flash point of diesel fuel is higher, it is a safer fuel to handle and store (unless it is contaminated with gasoline or alcohol). Diesel fuel's low volatility and high flash point are why diesel fuel pump islands often appear dirty and greasy. Diesel fuel is slow to evaporate while gasoline turns quickly to a vapor (**FIGURE 12-16**). A large spill of gasoline evaporates in minutes while spills of diesel fuel may take days or weeks to disappear. Heavier fractions of diesel fuel will take the longest time to evaporate.

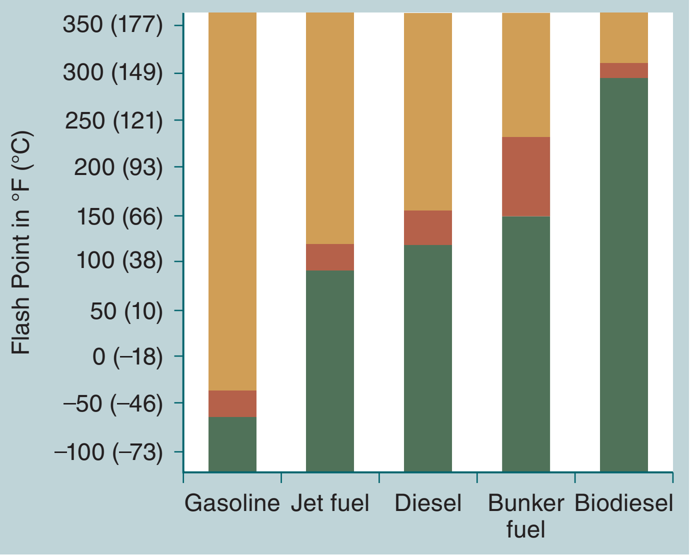

FIGURE 12-15 The flash point of diesel fuel is much higher than gasoline, making it safer to handle.

FIGURE 12-16 Unevaporated diesel fuel makes diesel fuel pump islands appear dirty and greasy.

Auto-Ignition Temperature

The **auto-ignition temperature** of diesel fuel is different from the flash point. This is the temperature at which a fuel will ignite when heated. No open flame is used to measure a fuel's auto-ignition temperature. The lowest auto-ignition temperature permissible for diesel fuel sold in North America is 292° F (144° C). Typically, diesel fuel ignites at temperatures of 392–482° F (200–250° C). Ignition temperatures are even lower when fuel is pressurized together with air in the combustion chamber. Note again that although gasoline is more volatile and possesses a lower flash point than diesel fuel, it has a higher auto-ignition temperature (**FIGURE 12-17**). Practically speaking, this means that if even a small quantity of gasoline is mixed with diesel fuel, it results in a fuel with a longer ignition delay time and causes excessive combustion noise, significant exhaust smoke, and other problems, such as fuel dilution and damaged engine components.

SAFETY TIP

Mixing alcohols or gasoline with diesel fuel is not only a dangerous practice but also harmful to the engine and fuel system. Both contaminants lower the flash point and CN of the fuel. This means the fuel will produce a vapor that ignites easier if exposed to an open flame and will become more hazardous to store and handle. Alcohols are also reactive and can cause corrosion to metal within the fuel system and lower the lubricating capabilities of diesel fuel.

Volatility

Volatility refers to how easily a liquid will convert to a vapor. Measuring volatility is a function of the quantity or percentage of fuel that evaporates at a particular temperature. Because diesel fuel has a mixed number of hydrocarbon fractions, lighter fractions of smaller, less complex fuel molecules convert to vapor at lower temperatures while increasingly heavier fuel fractions vaporize at higher temperatures. This explains why diesel fuel boils at a wide range of temperatures between 302–662° F (150–350° C) and not over a narrow temperature range. Volatility is expressed as a percentage of the fuel evaporating between those boiling temperatures. For example, to express the 90% volatility standard of 2-D fuel, 90% would be evaporated at 550–650° F (288–343° C).

Evaporative emissions systems are not required on diesel-fueled vehicles because of the fuel's low volatility. Even in warm weather, the vapor pressure that diesel fuel vapors exert inside a storage tank is insignificant when compared to gasoline (**FIGURE 12-18**).

▶ TECHNICIAN TIP

Diesel fuel filling stations may often have a lingering odor of diesel fuel because of the fuel's higher flash point and distillation temperature. A diesel fuel spill takes days to vaporize and dissipate, unlike gasoline, which only takes minutes.

Pour Point and Cloud Point

Pour point and cloud point refer to the two different temperatures that wax molecules in fuel crystallize. As the name suggests, **cloud point** is the temperature at which wax begins to give fuel a hazy or milky appearance. Pour point is the temperature at which diesel fuel thickens, called the *fuel-gelling phenomenon*, and no longer pours. When fuel reaches pour point, it cannot pass though lines and filters (**FIGURE 12-19**). Pour point occurs at a lower temperature than cloud point.

While some engines may fail to run at cloud point temperature due to filter plugging with wax crystals, all engines will

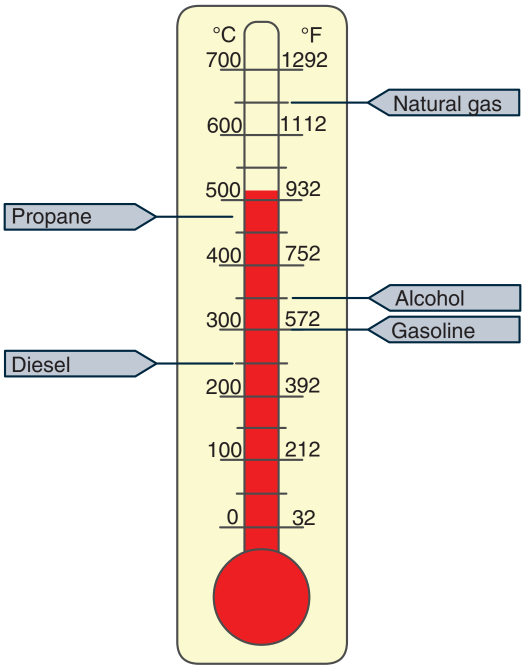

FIGURE 12-17 The auto-ignition temperature of diesel fuel is lower than that of gasoline and gaseous fuels. This means diesel fuel ignites sooner inside a pressurized combustion chamber.

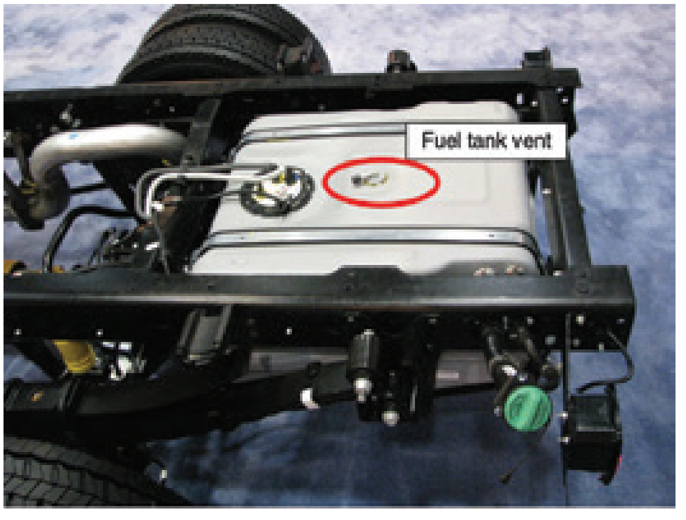

FIGURE 12-18 Unlike gasoline tanks, diesel fuel tanks are vented directly to the atmosphere because diesel fuel has low volatility.

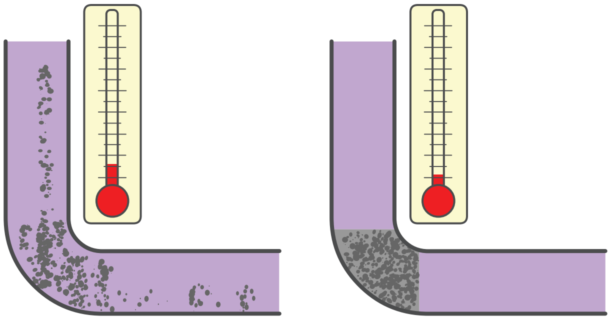

FIGURE 12-19 Cold temperatures will cause the wax content of diesel fuel to form crystals at cloud point and to congeal at pour point.

TABLE 12-3 Cold-Flow Properties of Three Grades of Diesel and Biodiesel

Diesel Fuel	Cloud Point	Pour Point	Cold Filter-Plugging Point
2-D	5° F (−15° C)	−31° F (−35° C)	−4° F (−20° C)
B100 (canola formulated)	26° F (−3° C)	25° F (−4° C)	24° F (−4° C)
B100 (soybean formulated)	38° F (3° C)	25° F (−4° C)	28° F (−2° C)

fail to operate at pour point temperature. The temperature at which fuel filters plug with wax and prevent fuel flow and engine operation is also called *cold filter plugging temperature*. The differences between cloud and pour point vary with the source of fuel and the use of additives but are typically 20° F (−7° C) apart. Without additives and conditioners, the cloud point for 2-D fuels can be expected to occur at approximately 40° F (4° C) and the pour point at 15–20° F (−9 to −7° C). Again, the source of the fuel and the refining methods used will generate a significant variance in these two temperatures. In a cold climate, winterized fuel is often made from a blend of 1-D and 2-D or Jet-A, which is designed to operate at high altitudes in very cold temperatures. Diesel 1-D has a lower pour point than 2-D, which allows it to move through lines and filters easier, but it also has a lower viscosity, which means it can leak more easily past operating clearances between high-pressure injection system components. Low-power complaints can occur with the use of winter-grade fuel because it has less energy content. The cloud and pour points of different grades of diesel and biodiesel vary (**TABLE 12-3**).

To operate diesels year-round and in cold temperatures, the properties of diesel fuel are adjusted throughout the year according to historical temperature data of the region where the fuel is sold. For example, in Ontario, Canada, a "Muskoka blend" is prepared for southern Ontario winters and an "Arctic blend" is used in northern Ontario. In Ontario, the months of April and September are the times when refineries make seasonal adjustments to cloud and pour point properties.

Lubricity

Lubricity refers to a fuel's lubricating quality. Many fuel system components rely on the lubricating properties of the fuel to prevent "galling" (i.e., the scarring of metal surfaces between moving metal parts) and seizure of moving parts. It is important that fuel have good lubricating properties to enhance the fuel system's durability. Compounds such as fats and waxes that are already naturally present in diesel fuel provide the lubricating properties of diesel fuel.

A Scuffing Load Ball-on-Cylinder Lubricity Evaluator (SLBOCLE) test evaluates a fuel's ability to lubricate, which is expressed in grams of load. The higher the SLBOCLE value, the better the lubricating ability. Another test that determines lubricity is the High Frequency Reciprocating Rig (HFRR). This test measures the depth and width of a scar left on a metal surface after repeated friction with another metal instrument. Depending on the lubricating properties of a fuel sample, a larger or smaller scar is produced. Contemporary fuel system moving parts that are only lubricated with fuel are hardened using silicon carbide steel-ceramic alloys. One marketing name for these alloys is diamond-like coating (DLC). Cutting tips for metal machining tools are also made from this material.

▶ TECHNICIAN TIP

Removing sulfur from diesel fuel does not directly cause fuel to lose lubricating qualities. Unfortunately, the process used to remove sulfur from diesel fuel in North America also removes fatty and wax-like molecules from the fuel that give it its natural lubricating qualities. Low-sulfur diesel (LSD S-500) and ultra-low–sulfur diesel (ULSD S-15) fuel are associated with greater fuel system component wear. Manufacturers have hardened fuel system components with a variety of ceramic alloy steels to better withstand the effects of the poorer lubricating properties of fuel with lower sulfur content.

Kinematic Viscosity

Viscosity refers to liquid's resistance to flow. High viscosity means the liquid is thick and slow flowing; low viscosity means the opposite. Fuel viscosity is commonly measured in units called *centistokes*. The higher the centistoke measure of a liquid, the thicker and more viscous it is. For example, water has a centistoke value of 1 and 20W oil is 4.3 centistokes. Fuel viscosity affects injector lubrication and fuel atomization (**FIGURE 12-20**). Fuels with low viscosity may not provide adequate lubrication for the close clearances of precision-fit fuel system components because parts are separated with only thin, lubricating film barriers. On the other hand, if fuel viscosity is too low, it can easily leak and slip around the high-pressure system's plunger and barrels. The result is that less fuel is injected, which reduces power output and increases wear of the fuel system components. Fuels that are too thick, or viscous, will also cause performance-related complaints due to reduced flow rates.

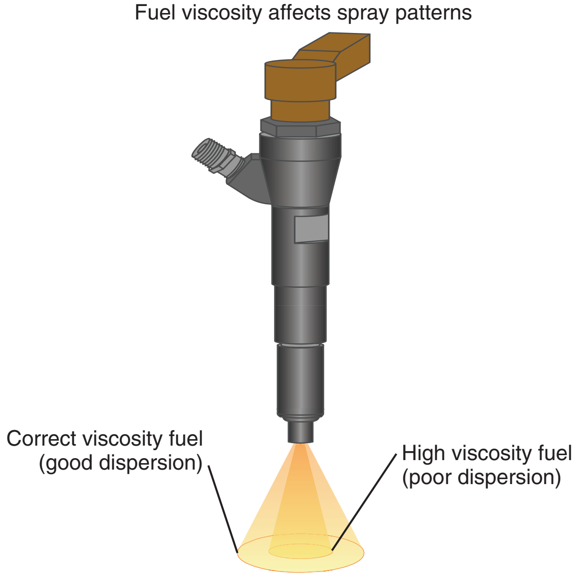

FIGURE 12-20 Fuel viscosity can affect the spray pattern and fuel droplet size from an injector. Highly viscous fuel will not atomize well and will negatively affect combustion quality.

Because fuel atomization is affected by fuel viscosity, fuel with high viscosity forms larger droplets during atomization. Larger droplets take longer to burn and mix poorly with air, which leads to poor combustion quality and increased exhaust emissions.

Mixing Gasoline and Diesel Fuel

Gasoline and diesel fuels should never be mixed. Even 1% or less gasoline will lower the flash point of diesel fuel blend below its minimum specification. Contamination at 1% can affect engine performance, and the fuel is more hazardous to handle (**TABLE 12-4**).

Occasionally, due to a poor understanding of fuel properties, an incorrect recommendation is made to mix gasoline or alcohol and diesel fuel together to minimize fuel gelling and improve combustion quality in cold-weather operations. There are several problems with this. First, while gasoline and alcohols do have an antigelling effect on diesel fuel, they reduce diesel fuel lubricity. Reduced lubricity will increase fuel system wear and shorten fuel system life. Second, the cetane number and octane number or ignition qualities of these fuels are inversely related to one another. Gasoline contamination, even in small amounts, will dramatically reduce diesel fuel CN and its ability to ignite, lengthening the ignition delay period and causing severe engine knock. This is why gasoline contamination of diesel fuel produces a lot of smoke, causes engines to run roughly, and increases engine noise. Diesel fuel that is mixed with gasoline or alcohol does not have enough time to completely burn because ignition begins much later in the combustion cycle. The pressure spike caused by prolonged ignition delay will even break glow plugs and possibly cause other engine damage related to fuel dilution of engine oil from unburned fuel. Another significant effect is that diesel fuel mixed with gasoline will not vaporize quickly, causing poor engine performance. Last, gasoline has a higher ignition temperature than diesel, which contributes to further ignition delay. While some may think that mixing diesel fuel with more highly volatile gasoline will improve a diesel's ability to start, the opposite is true. Gasoline needs more heat to convert to a vapor in the combustion chamber, which produces a longer ignition delay period.

TABLE 12-4 Ignition Quality of Gasoline and Diesel Fuel

Property	Gasoline	Diesel
Flammability limits (volume in air)	1.4–7.6%	0.6–5.5%
Auto-ignition temperature	700–800° F (371–427° C)	600° F (316° C)
Temperature flash point	−45° F (−43° C)	100–125° F (38–52° C)

▶ **TECHNICIAN TIP**

If diesel fuel is accidentally contaminated with gasoline, all fuel should be drained from vehicle storage tanks, lines, and filters. After replacing the contaminated fuel with good-quality diesel fuel, the engine lube oil should be changed if the engine has been operated even briefly with contaminated fuel. This step is needed because engine misfires and poor combustion quality will quickly dilute engine oil with unburned fuel, after it has washed down the cylinder walls and entered the crankcase oil.

ASTM Diesel Fuel Grades

LO 12-5 Identify and describe ASTM grades and applications used to select petroleum and biological-based fuels according to operating conditions.

To a large extent, diesel engine development has been dependent upon the development of fuels that contribute to reliable operation and satisfactory performance. The ASTM is responsible for diesel fuel specifications and test methods for petroleum-based diesel fuel and biodiesel fuel (see the *Biodiesel Fundamentals* section of the chapter). These specifications are defined and explained in ASTM standard D975, and they can differ in characteristics such as sulfur content, flash point, and auto-ignition temperatures (**TABLE 12-5**).

ASTM fuel grades are used to help select the correct fuel for an application. Because diesel fuel is consumed by different kinds of on- or off-highway vehicles, agricultural equipment, railroad locomotives, and marine vessels (such as river barge tugs, pleasure craft, and ocean-going vessels), among others, there is no one grade to fit all vehicles. Special diesel fuels are also used for stationary engines to power irrigation equipment and emergency generators, such as those that hospitals rely on during a power outage. Fuel in these applications tends to turn over slowly, meaning it can sit and deteriorate before the engine consumes it.

TABLE 12-5 Specifications for Diesel Fuel Grades and Gasoline

Diesel Fuel Grade	1-D Low Sulfur	2-D Low Sulfur	B100 Biodiesel	2-D ULSD	Gasoline	4-D
Auto-ignition temperature	350–714° F (177–379° C)	490–545° F (254–285° C)	550° F (288° C)	604–662° F (318–350° C)	700–840° F (371–449° C)	N/A
CN[a] (minimum)	40	40	48–65	40	N/A	30
Flash point (minimum)	100° F (38° C)	126° F (52° C)[b] 109° F (43° C)[c]	302–338° F (150–170°C)	266° F (130° C)	−49° F (−45° C)	131° F (55° C)
Heat value	135,000 Btu	140,000 Btu	117,000 Btu	134,000 Btu	124,000 Btu	N/A
Aromatic content by volume (maximum)	35%[d]	35%[d]	N/A	27–32%	N/A	N/A
Sulfur content (by weight)	0.05%	0.05%	N/A	0.0015%	N/A	2.00%
Water content (by weight)	0.05%	0.05%	0.05%	0.05%	N/A	0.50%
Distillation temperature[e]	550° F (288° C)	730° F (388° C)	680° F (360° C)	730° F (388° C)	N/A	N/A
Viscosity at 104° F (40° C) (maximum)[f]	1.3–2.4 cSt	1.9–4.1 cSt	4.7–6.0 cSt	1.9–4.1 cSt	N/A	13.1–29.8 cSt
Density at 59° F (15° C)	6.76 lb/gal (810 g/L)	7.05 lb/gal (845 g/L)	7.328 lb/gal (878 g/L)	7.206 lb/gal (863 g/L)	6.14 lg/gal (736 g/L)	N/A
Lubricity (BOCLE)[g]	0.018" (460 microns)	0.018" (460 microns)	0.012" (312 microns)	0.018" (450 microns)	N/A	N/A
API rating	35–40	26–37	28–40	32–37	56–59	N/A
Reid vapor pressure at 100° F (38° C)	N/A	<0.2 psi (<1.4 kPa)	<0.04 psi (<0.028 kPa)	N/A	8–15 psi (55–103 kPa)	N/A

a. See the cetane number section
b. May through October
c. November through April
d. 90% volume recovered
e. 10% California Air Resource Board standard in California
f. The HFRR test is at 140° F (60° C); cSt stands for centistoke, the standard measurement for viscosity
g. Ball-on-Cylinder Lubricity Evaluator (BOCLE) measures scar diameter; fuels with lower numbers have better lubricating properties

Grades of ASTM Diesel Fuel

Diesel fuel is also classified according to its viscosity and density. As discussed earlier in this chapter, commercially available diesel fuel is numbered as 1-D, 2-D, and 4-D, with 1-D being less dense and viscous and 4-D being the heaviest and most viscous.

- 1-D is usually a special purchase by bulk users such as transit fleets and municipalities with their own fuel distribution systems. It is preferred whenever the lowest emissions output and superior cold-weather performance are required.
- 2-D is the most common grade of diesel fuel available for retail. The higher heat content of 2-D provides better fuel economy, and more 2-D is produced from a single barrel of oil than 1-D, which translates into lower prices at the pump.
- 4-D is heating fuel for oil burner furnaces, but it can be tolerated by indirect injection combustion chambers. 4-D has numerous other properties that make it undesirable for use as an engine fuel. Because it is not taxed like 1-D and 2-D, it is not permitted to be used by on-highway vehicles and is not for sale at retail fuel pumps.
- Biodiesel is defined as a fat-based fuel made from vegetable and animal sources. Pure biodiesel is termed B100, with "B" designating it as biologically derived and "100" as the percentage of bio-based source. A 20% mixture of biodiesel with conventional diesel would be identified as B20. Biodiesel is most commonly blended with conventional diesel fuel, and it is uncommon to see B100 at retail fuel pumps. (See the *Biodiesel Fundamentals* section of the chapter.)

Prior to 2010, many engine manufacturers did not perform testing of engines using biodiesel. Failures caused by or attributed to the use of the fuel above a B5 blend were not covered by warranty. Engines built since 2010 are required by legislation to be compatible with B20 fuel and certified for emissions compliance using B20 fuel.

Determining the ASTM Grade of Fuel

Determining the ASTM grade and API number of a fuel is an important starting point when diagnosing low-power complaints. Seasonally blended fuels with low density and prepared for colder seasons and regions will not have the same energy content or characteristics as fuels prepared for warmer seasons and regions. Low-density fuels also typically have low fuel viscosity, which can allow fuel to leak more easily past clearances between plungers and barrels in high-pressure injection systems, which results in reduced fuel delivery. To determine the grade and density of fuel, a temperature-compensated hydrometer is used, which measure a fuel's API number (**FIGURE 12-21**, **TABLE 12-6**).

To determine a fuel's ASTM grade, follow the steps in **SKILL DRILL 12-1**.

Biodiesel Fundamentals

Diesel engines can not only burn fuel made from petroleum oils but also fuels made from biological sources such as animal fat or plant matter. Some diesel engines will even run using pure vegetable oil for fuel. Because legislation requires the use of more renewable fuels, the use of biodiesel is expected to become more widespread. Many countries have now mandated the use of biodiesel fuel. In the United States for example, the **Renewable Fuel Standard (RFS)**, part of the **Energy Independence and Security Act (EISA)** of 2007, encourages the use of biofuel by requiring manufacturers to certify engine emissions compliance using B20 biodiesel fuel in addition to petroleum fuel. The EISA also requires that 30% of all fuels originate from renewable sources by 2022. Prior to 2011, almost all manufacturers endorsed the use of B5 blends of fuel, but B20 biodiesel was also available. Pure biodiesel may be used as fuel (such as B100) or blended with petroleum diesel to add the beneficial characteristics of biodiesel to petroleum diesel (such as B5 and B20).

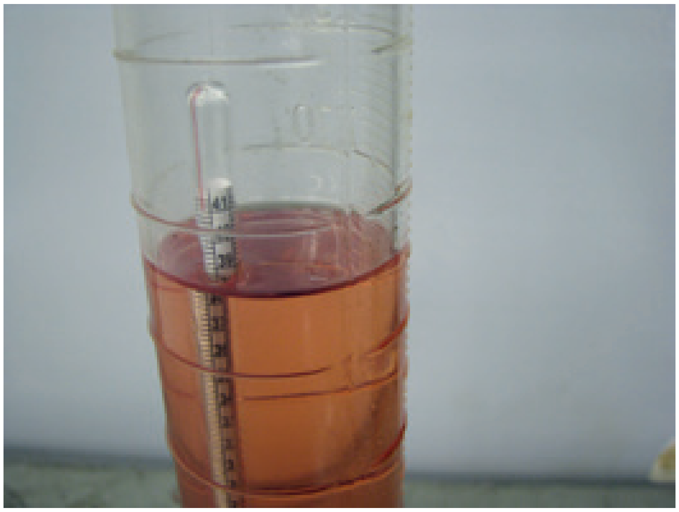

FIGURE 12-21 Reading the API number from the hydrometer.

Biodiesel Advantages

Biodiesel offers a number of benefits, both economically and environmentally, for energy security, job creation, agriculture, rural development, energy supply, and public health. Although there are drawbacks, studies indicate that biodiesel can achieve as much as a 78% reduction in the amount of carbon dioxide (CO_2), a greenhouse gas, over the life cycle of production and use. This estimate is based on the assumption that CO_2 is trapped in plant matter grown to produce biodiesel. Production of biodiesel requires more energy input than petroleum-derived diesel fuel; however, biodiesel yields 3.24 units of energy for every 1 unit of biodiesel consumed during production. Additional benefits of biodiesel include:

- It is a renewable resource.
- It is biodegradable.
- It is not toxic to the environment if spilled.
- It contains no sulfur.
- No engine modifications are required to use it.
- It produces lower hydrocarbon (HC), CO, and PM emissions than petroleum-based diesel.
- It has enhanced lubricating properties in comparison with LSD and ULSD petroleum diesel.
- It has no aromatic content.
- It has a naturally high CN, a measure of the ignition quality of fuel.

TABLE 12-6 Determining a Fuel's ASTM Grade

ASTM Grade	API Number	Density	Btu Heating Value
1-D	38–45	6.675–6.950 lb/gal (800–833 g/L)	132,900–137,000 per gallon (35,108–36,192 per liter)
2-D	30–38	6.960–7.296 lb/gal (834–874 g/L)	137,000–141,800 per gallon (36,192–37,460 per liter)
4-D	20–28	7.396–7.787 lb/gal (886–933 g/L)	143,100–148,100 per gallon (37,803–39,124 per liter)

SKILL DRILL 12-1 Determining a Fuel's ASTM Grade

1. Obtain a fuel sample from the vehicle or equipment fuel tank and place the sample in a graduated cylinder.
2. Using a purpose-made **fuel hydrometer**, measure the fuel's temperature and API number.
3. Using a chart provided by the hydrometer's manufacturer, look up the temperature-corrected API number for the fuel. Because the density of a fuel is affected by temperature, the corrected API value provides the API number that the fuel would have at room temperature.
4. Using the ASTM standard, compare the API number with the ranges for 1-D, 2-D, and 4-D ASTM grades of fuel.
5. Report the information on a worksheet or work order.

Biodiesel Performance

Operationally, biodiesel performance is similar to conventional diesel in terms of power, torque, and fuel consumption without any modification to the fuel system. Biodiesel can also be blended into petroleum-based diesel, and for the most part, no engine modifications are required to use blends of biodiesel and petroleum diesel. The shape and composition of biodiesel fuel molecules provide other advantages that make it appealing as an alternative to conventional diesel fuel. These advantages include:

- Biodiesel has no sulfur content, which means fewer emissions and increased engine longevity.
- Biodiesel has no aromatic content, which improves emissions and reduces the risk of carcinogens.
- Biodiesel has about 11% oxygen content (petroleum-based diesel contains no oxygen) for improved combustion characteristics.
- Biodiesel has a naturally higher CN, commonly 50–55.
- Biodiesel has better lubricity. Conventional diesel fuel has a minimum standard of 109 ounces (oz; 3090 grams [g]) SLBOCLE, whereas biodiesel has 176 oz (4990 g). Even mixing biodiesel with conventional fuel in a concentration as low as 1% can improve lubricity by 65%.
- Biodiesel has a higher flash point, which means the fuel is safer to handle.
- Because biodiesel is made from vegetable oil or animal fat, it is comparable to table salt in toxicity and biodegrades as fast as sugar. This means it is not hazardous to the environment if it is spilled or leaks from an underground storage tank.
- Biodiesel has favorable emissions characteristics (**FIGURE 12-22**). Biodiesel fuel has been rigorously evaluated for its production of emissions and potential health effects, as required of all alternate fuels by the EPA under the Clean Air Act.

Using B100 fuel, for example, will result in the following emissions benefits:

- A 67% reduction in unburned HCs
- A 48% reduction in CO
- A 47% reduction in PM emissions

▶ TECHNICIAN TIP

Before switching to biodiesel, technicians should check with a vehicle manufacturer to ensure that materials used in the fuel system are compatible with biodiesel use. When biodiesel fuels are used in vehicles built prior to 2010, seals, hoses, gaskets, and even wire coatings exposed to fuel, such as those in some injection pumps and fuel-level sensors, require regular monitoring. Currently, vehicle manufacturers will repair fuel-related failures under warranty only if B20 or less fuel (conventional diesel plus less than a 20% mixture of biodiesel) is used.

Biodiesel Disadvantages

While biodiesel has many advantages, it also has certain disadvantages, including:

- **Cost:** Biodiesel is currently more expensive than petroleum diesel fuel due to the oil content of its sources, such as the soybean, which is only 20% oil.
- **Fuel system incompatibility:** Biodiesel is an excellent solvent and leaves fuel systems cleaner. However, biodiesel fuel can damage some types of rubber found in fuel hoses, gaskets, and wire insulation used in some vehicles, particularly in vehicles built before 1994. Currently, fuel system part manufacturers are switching to components suitable for use with low-sulfur and biodiesel fuel.

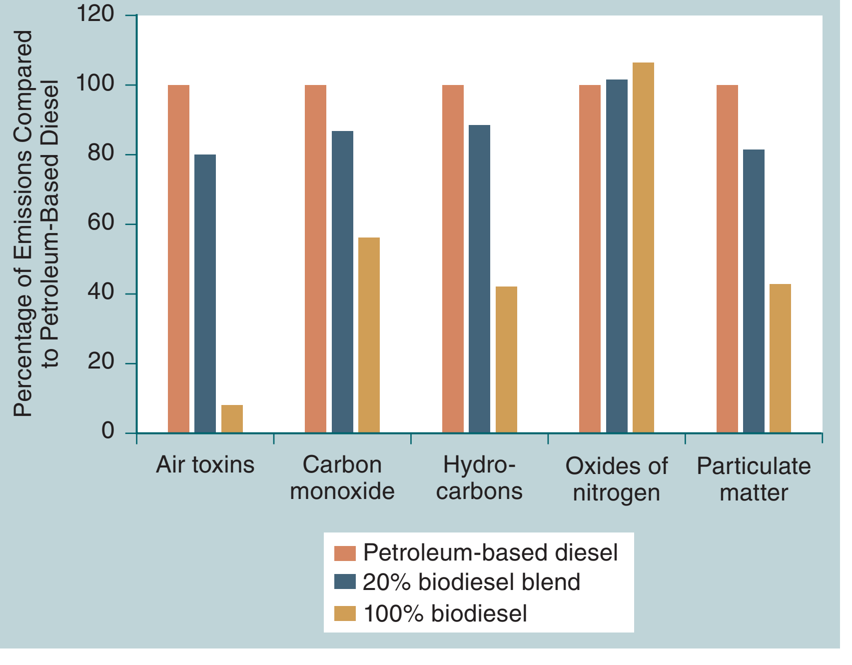

FIGURE 12-22 Biodiesel generally produces fewer noxious emissions compared with conventional diesel fuel. Note the increase in NOx emissions with biodiesel.

- **Filter plugging upon switching:** Plugging typically occurs when switching from conventional diesel fuel to biodiesel. Due to the solvent action of biodiesel, the dirt removed can quickly foul filters, which should be changed several hours after engine operation.
- **Distribution infrastructure:** Biodiesel is not distributed as widely as traditional petroleum diesel. Production, blending, and distribution are performed on a smaller scale than conventional petroleum diesel. However, distribution infrastructure is improving, and many fleets use a blend of biodiesel for their operations.
- **American Petroleum Institute (API) standards:** Despite attempting to meet ASTM D6751 standards, numerous problems with biodiesel stem from its manufacturing processes. For example, if too much **methanol** is used, it will cause corrosion of aluminum and zinc components in the fuel system.
- **Aromatic content:** Because there is no aromatic content in biodiesel fuel, it can potentially cause some types of rubber and elastomer components to crack and deteriorate. However, the fuel contains other fat and wax molecules that can maintain seal and gasket firmness.
- **Heat content:** Biodiesel has less heat content than petroleum diesel fuel. Fuel economy can be reduced by as much as 10% for pure biodiesel.
- **Pour point:** Biodiesel has a higher pour point (5–10° F [–15 to –12° C]) than conventional diesel fuel. This means it can thicken and gel more readily in cold weather. To remedy this condition, biodiesel can be blended with conventional 2-D or 1-D diesel fuel. Biodiesel can also be treated with pour point depressants (fuel system heaters and heated storage are also recommended).
- **Shelf life:** The shelf life of biodiesel is not as long as conventional diesel. What makes biodiesel biodegradable also makes that biodiesel fuel, in its pure form, unstable. Its acid content increases over time, which can damage metal components. Fuel aging is also accelerated in the presence of heat, oxygen, water, and metal ions. Storage of biodiesel for longer than 6 months is not recommended. If biodiesel is stored for longer than 6 months, it should be reevaluated to ensure that it meets ASTM D6751.
- **Polymerization (gelling) of engine oil:** The most serious problem with the use of biodiesel is its effect on engine oil. On engines built in 2007 and later that are equipped with DPFs, which are actively regenerated by an additional injection event during the exhaust stroke, some fuel will cling to the cylinder walls. Rings will sweep the fuel into the oil, where it will accumulate, because the higher flash point of biodiesel will not allow it to boil out of oil like petroleum-based fuel. The fuel will cause chemical changes to take place in the oil that will link up chains of hydrocarbons and turn the oil into gel. Lacking proper lubrication, the engine will catastrophically fail. The biodiesel also attacks an important oil additive: zinc disulfide. Even before the engine is damaged, the oil loses some of its lubricating properties. Dosing the DPF using an external fuel dosing valve located in the exhaust system downstream or after the turbocharger is the solution for this problem.

Biodiesel and Oxides of Nitrogen Emissions

One notable exception to the emissions benefits of biodiesel is that it can produce higher levels of NOx from some engine families. Because engines built prior to 2010 were not certified to operate using biodiesel, some engines may produce more NOx emissions using biodiesel than conventional petroleum-based diesel.

Production of Biodiesel

Biodiesel is primarily manufactured from seeds or grains. Such vegetable oil sources include peanuts, soybeans, rapeseeds (i.e., canola oil), cottonseeds, safflower seeds, linseeds, corn, and sunflower seeds, among others. Animal fats such as beef tallow and recycled cooking oil are also used in some formulations.

For biodiesel derived from soybeans and other like sources, the vegetable oil is typically extracted from grains after crushing them and separating solids from oils using solvents such as hexane. Gummy substances and impurities are removed by mixing the oil with 2–3% water and then heating it to 122° F (50° C) while mixing the material. Heavier gums, water, and impurities will settle out of the mixture, and the process of removing the fatty acids for fuel production can take place. In this step, the vegetable oil is reacted with an alcohol such as methanol or **ethanol** using a catalyst (**FIGURE 12-23**).

Straight Vegetable Oil Biofuel

Straight vegetable oil (SVO), or unrefined vegetable oil, poses two problems when used as an acceptable alternate biodiesel fuel source. First, it can lead to coking of the injectors. Coking is the buildup of carbon in the injector nozzle that then leads to reduced fuel flow and irregular injector spray pattern. Second, at approximately eight times the viscosity of conventional diesel fuel, SVO is too viscous to move easily through lines, filters, and other fuel system components. Heating the fuel to thin it out is one solution to this problem (**FIGURE 12-24**). Another solution is to remove glycerin from the vegetable oil molecule and replace it with an alcohol molecule, which is what happens during the process of transesterification—another name given to the biofuel production process.

Transesterification

Several techniques are used to convert animal fats and vegetable oils into biodiesel fuel. Even algae are considered a viable source of oil to produce biofuels. Microproducers of biofuels range from small companies to individuals and use unique processes, base stocks, and formulations to make biodiesel fuel for agricultural use and even for private home use.

In the most common method to produce "backyard" biodiesel, methanol alcohol is mixed with vegetable oils and glycerin is replaced with alcohol. A catalyst such as sodium or potassium hydroxide speeds this process. The glycerin separates from usable fuel in the oil and forms sediment. Replacing the glycerin

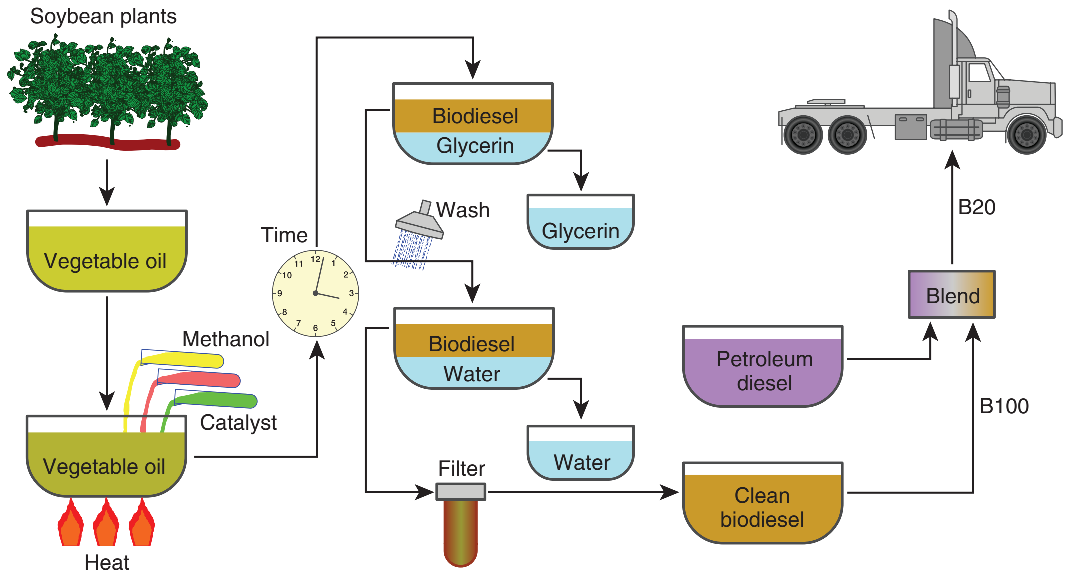

FIGURE 12-23 The basic steps used to convert vegetable oils into usable biodiesel.

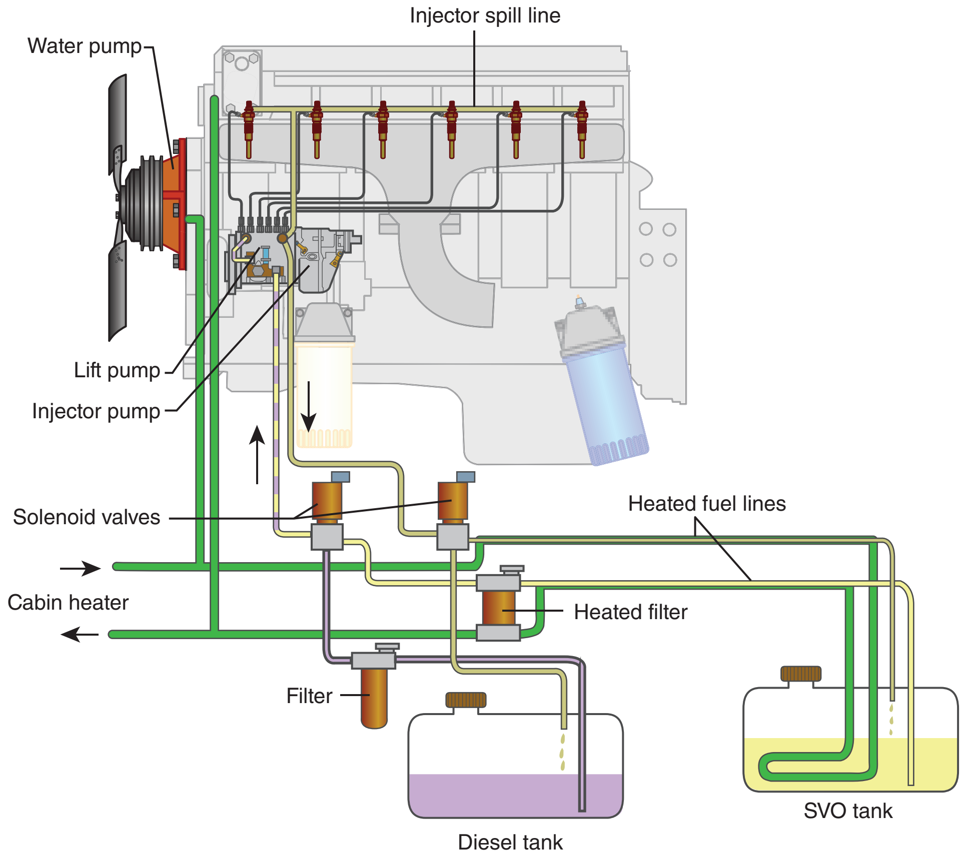

FIGURE 12-24 A typical low-pressure fuel system configuration for using SVO as a fuel source. The oil requires heating to reduce its viscosity to that near diesel fuel.

with alcohol molecules is a process called **transesterification**, which is the substitution of methanol for fatty acids to change the oil into fuel. **Fatty acid methyl ester (FAME) fuel** is another name for biodiesel produced through transesterification. It is important to remember that FAME processes that use potassium hydroxide or sodium hydroxide as a catalyst can cause fuel system corrosion, injector plugging, and deposit formation if any catalyst is left in the fuel.

Diesel Fuel Additives

LO 12-6 Describe and explain the purpose, functions, and characteristics of diesel fuel additives.

A wide variety of diesel fuel additives are used to improve the general quality and performance of diesel fuel when fuel quality is compromised. Normally, when clean, good-quality fuel is used, there is no need to add anything to fuel. Nevertheless, many aftermarket additives are sold to meet many different applications. Most of these products are marketed to add to the diesel fuel and give users the expectation that they will improve engine performance and decrease fuel consumption. It is important to note that if the additive contains cetane booster, the formulations tend to be highly concentrated and a little goes a long way (**FIGURE 12-25**).

▶ **TECHNICIAN TIP**

Many fuel producers and original equipment manufacturers do not recommend the use of any fuel additives when it is good-quality, fresh fuel purchased from a reliable retailer.

Additive Maker Claims

In the United States, all manufacturers of fuel additives must register their product with the EPA, who then evaluates the products for adverse human health or negative environmental impact. Registration with the EPA does not substantiate marketing claims made by additive manufacturers. Many claims made by additive manufacturers cannot be proven. For example, a group of popular combustion catalysts, which claimed to increase fuel economy and lower emissions, were evaluated by an independent research facility and were revealed to show no significant differences in fuel economy or exhaust soot levels. Such results are not surprising because diesel engine combustion efficiency is typically greater than 98%, even when using fuel without additives. If it is believed that an additive is necessary, thoroughly research the product before it is purchased and used.

FIGURE 12-25 Additives are generally used sparingly. This 32 oz (1 L) bottle treats almost 250 gal (946 L) of fuel.

Types of Additives

The large number of available additives can be grouped according to function (**TABLE 12-7**). Four major categories include:

- Engine performance enhancers
- Fuel stability
- Fuel handling
- Contaminant control

Cetane Boosters

Cetane boosters, also called *ignition accelerators*, are supposed to reduce combustion noise and smoke, improve starting in cold weather, and increase acceleration response. Boosters accomplish this by increasing the CNs of diesel fuel. This means fuel will ignite and burn faster. By minimizing the ignition delay, improvements to cold starting and acceleration, along with reduced smoke emissions, are accomplished. User reports indicate that overconcentration of cetane boosters can also produce the opposite effects—excessive exhaust smoke emissions, low power, and poor fuel economy.

The majority of these CN booster compounds are nitrate based, which can increase the CN of the fuels by as much as

TABLE 12-7 Fuel Additive Types and Benefits

Additive	Benefit
Cetane number boosters	Improve ignition quality by increasing the CN for improved starting and reduced white smoke
Lubricity improvers	Improve lubricating properties of fuel
Detergents, dispersants, and antioxidants	Prolong storage life; minimize oxidation; reduce gums, resins, and sediments; and improve injector spray patterns
Stabilizers	Inhibit oxidation to extend storage life
Metal deactivators	Deactivate metal ions, such as copper compounds in fuel, to promote storage life
Biocides	Minimize bacteria and fungi growth, which helps prevent fuel filter plugging
Pour point depressants	Lower temperature operation Improve cold-flow properties Reduce pour and cloud point
Defoamers	Reduce foaming when filling tanks and transferring fuels through pipelines
Smoke suppresants	Promote more complete combustion and reduce exhaust smoke
Rust inhibitors	Reduce formation of rust in fuel storage

seven points in small concentrations (0.2%). Cetane boosters may be added by fuel refiners or end users.

▶ TECHNICIAN TIP

More of a good thing is not always better. Excessive concentration of fuel additives in fuel can cause adverse and unintended changes to fuel chemistry. For example, overconcentration of some cetane boosters may cause excessive black smoke. Some additives will damage fuel system materials, such as elastomer seals and nylon components.

Detergents

Fuel and crankcase lubricants can leave gummy carbon deposits in the fuel system that can decrease engine performance. This is especially true of nozzle valve deposits. Detergent additives operate as solvents to dissolve deposit-forming resins, allowing them to be flushed through the fuel system. Optimal concentrations of detergents are typically 50–300 ppm.

Detergent additives are also used to treat asphaltene, a contaminant that is increasingly common as refineries use new methods to increase yield from a barrel of oil (**FIGURE 12-26**). Asphaltene formation increases when fuel is stored for a long period of time and then heated after circulating through an engine. Asphaltene can cause abrasive wear and fuel filter plugging (**FIGURE 12-27**).

Lubricity Additives

When fuel is severely hydrotreated to remove sulfur, other compounds, which provide lubricating properties, are also removed. The service life of injection pumps, injectors, fuel transfer pumps, and other fuel system components can be prolonged by using lubricity additives.

Smoke Suppressants

A number of products have been used to minimize black smoke. In the 1960s, a barium-based substance was used before the Clean Air Act became effective. This compound was later banned because of concerns about the human health impact of barium. Other suppressants, such as cerium or platinum, have been added to fuel as combustion catalysts, although the EPA has not yet approved these.

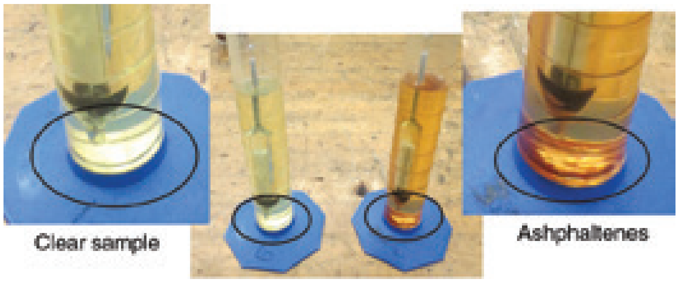

FIGURE 12-26 Ashphaltenes are small, hard particles of asphalt that develop in diesel fuel when it is exposed to high temperatures for an extended time period. Stagnant fuel will also develop ashphaltenes.

FIGURE 12-27 Asphaltene detergent conditioner dissolves small, hard crystals of tar-like asphalt compounds in diesel fuel.

Fuel-Handling Additives

End-user applications of these additives are primarily for de-icing and as pour point depressants. At refineries, additives to minimize fuel foaming and reduce drag in pipelines are also used. Some of these additives, used by even large corporations, have been discovered to have detrimental effects over the long term on materials used in the high-pressure injection components of fuel systems. Antifoaming additives are used to minimize foam while filling fuel tanks.

De-Icing Additives

Diesel fuel is both hygroscopic and hydrophilic, which means it attracts and absorbs water (**FIGURE 12-28**). Because water dissolved in diesel fuel can freeze, fuel lines and filters can plug with ice. To prevent this, small quantities of glycol can be added to fuel. This substance dissolves in water rather than fuel, resulting in a lower icing temperature of water in diesel.

▶ TECHNICIAN TIP

Water is a fuel system's biggest enemy because it reduces lubricating ability and causes corrosion. Moisture will readily condense on cooler surfaces of diesel fuel, which subsequently absorbs water easily. Keeping fuel tanks topped off will minimize the condensation of warm, moist air inside a fuel tank. The best practice to prevent fuel from absorbing water content is to fill a fuel tank in the evening or late afternoon rather than in the morning. This prevents large quantities of warm, moist air from condensing in the fuel tank overnight when there are large changes in outdoor temperatures.

Pour Point Depressants

Paraffin is one of the major types of hydrocarbons that make up diesel fuel. At low temperatures, these wax molecules can clump

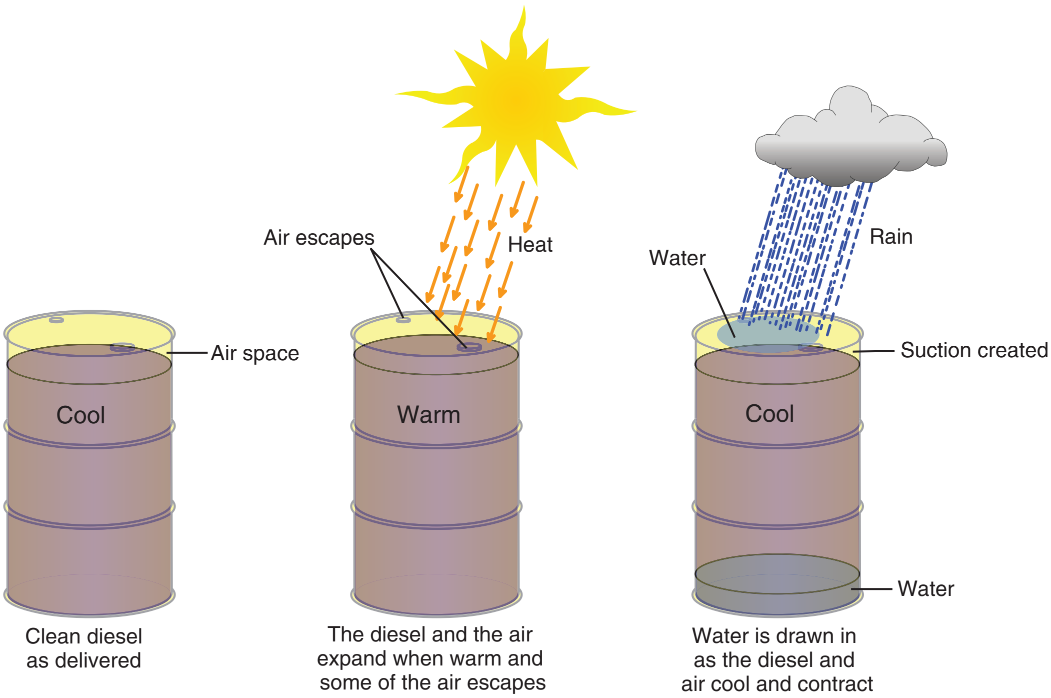

FIGURE 12-28 Diesel fuel will attract and dissolve water. Constant temperature changes during humid weather cause water to build up in fuel tanks.

together and eventually cause diesel fuel to cloud and gel. The typical temperature range at which fuels thicken and no longer flow is 6–10° F (−14 to −12° C) below the cloud point. To solve this problem, fuel can be blended with kerosene or 1-D. There are additives manufactured that can change the size and shape of wax crystal formation.

Fuel Stabilizers

After refining diesel fuel, chemical reactions between air and compounds in the fuel can take place. Heat will then speed up some of these reactions, which can lead to fuel darkening, formation of particles in the fuel, and general deterioration of fuel quality.

Fuel refineries use fuel stabilizers to reduce oxidation and other chemical reactions between compounds in the fuel. Dispersants can also be added to keep particles dissolved in fuel rather than clustered together, which will eventually foul and plug filters.

Corrosion Inhibitors

Because many fuel tanks and lines are made of steel, rusting and corrosion of the interior, as well as metal fittings and filter housings, can take place. Eventually, corrosion can penetrate steel walls and create fuel leaks. Rust particles can also plug fuel filters and cause abrasive wear to fuel system components. Corrosion inhibitors are compounds that form a barrier on metal surfaces that prevents chemical reactions between corrosive substances in the fuel.

Copper is another metal that diesel fuel should not corrode. Due to the sulfur content of diesel fuel, it can darken materials made of copper and bronze, forming a black, gooey coating on these parts. ASTM standard D975 has specifications for diesel fuel compatibility with copper.

Contaminant Control

Contaminant control additives are remedies to problems associated with prolonged fuel storage. Fuel can absorb water if it remains stagnant for long periods in humid conditions. As fuel absorbs more water and remains in suspension, it is referred to as *bound fuel*. Rusting and corrosion of fuel tanks can take place as fuel absorbs water where it remains either free or bound. Iron oxides are especially abrasive to close-fitting injection system components.

Biocides

Additives that control biological contaminants are also marketed. The most important and useful additives are **biocides**, which are poisons that kill bacteria and microorganisms that thrive in fuel that contains free water. Free water is water that is visible in fuel, which is unlike water that is bound or dissolved in fuel and is invisible. Typically, fuel that has been stored for prolonged periods in warm, humid climates is most vulnerable to this kind of contamination. When organisms are present inside a fuel tank or system, they can foul fuel filters and fuel lines.

Biodiesel Contamination of Engine Oil

After the introduction of low-sulfur fuels, biodiesel has been considered for use as a lubricity additive to keep moving parts operating smoothly inside fuel injection systems. The dilution of engine oil with biodiesel is another matter. Biodiesel promotes fuel dilution of engine oil to a much greater extent than petroleum-based fuel. Oil dilution with biodiesel occurs when a postcombustion injection of fuel into the cylinders is used to reduce combustion soot and regenerate a particulate trap or NOx adsorber. Heavier, less volatile fractions of fuel do not vaporize during postcombustion injection and liquid fuel clings to the cylinder walls. Because biodiesel has a higher boiling temperature, it tends to dilute the engine oil disproportionately to its blend ratio in the fuel.

Fuel passes by the pistons and accumulates in the crankcase. Once there, fuel polymerizes (joins together to form long, complex-shaped molecules) with oil and produces sludge. Engine damage can result from oil passageways blocked by sludge. Deposits also form in the ring-belt area of the piston, leading to ring stickage and increased crankcase blowby, which further aggravates oil contamination with increased levels of soot.

Raw or refined vegetable oils produce the greatest harm, but the harm may not become evident until a significant amount of damage has occurred over an extended period.

Petroleum-based fuel does not produce this effect at all because it readily evaporates when the oil is heated. Biodiesel blends higher than B20 will enable larger amounts of unburned fuel to slip by the piston rings and condense in the lubricating oil. Engine oil change intervals may need to be shortened significantly if blends of biodiesel higher than B20 are used.

Biodiesel also interferes with the action of zinc-based antiwear additives and detergents used in engine oil. Engine oil diluted with biodiesel can displace such additives on metals and chemically destroy the additive. This means that even before the engine oil thickens and turns to gel, lubricating oil diluted with biodiesel will begin to lose its ability to properly lubricate parts under extreme pressure.

Diesel Fuel Maintenance

LO 12-7 Recommend service and maintenance practices related to analyzing fuel quality.

Diesel fuel, whether it is petroleum derived or biodiesel, has specialized maintenance needs that the technician should take into consideration for the kinds of vehicles and engines that they maintain. Fuel suspected of causing problems can be analyzed by a technician or can be sent to commercial labs that specialize in fluid analysis for engines, hydraulic systems, and powertrains. Fuel analysis is a critical first step whenever complaints related to low-power performance, excessive emissions, and combustion noise are investigated. Fuel system failures that involve damage to injectors and other high-pressure injection system components, or when frequent failures are encountered, demands that fluid analysis be used as part of a comprehensive diagnostic inspection. Both fuel and lubricating oil should be analyzed when unusual conditions or failures related to the lubrication system are investigated. Lab analysis of fuel can be an especially crucial step when fuel is purchased in bulk. The operation of an entire company—both in costs and in efficiency—can be jeopardized by defective fuel and the consequences of its use.

Specific Gravity: American Petroleum Institute Index

For diesel service technicians, observational analysis of fuel quality can yield important clues about fuel quality and properties. This analysis begins by measuring the specific gravity or density of a fuel in a shop. Fuel density, while not a definitive measurement, is a good indication of the grade of fuel. Again, it is important to note that a fuel's CN can be determined only by lab analysis. Fuel density is an important property of fuel because it affects engine power and fuel economy. Less dense fuel, which has lower specific gravity, weighs less per gallon or liter than denser fuel and has less energy content. Viscosities of less dense fuel found in winter grades, 1-D, Jet-A, or blended fuels not only interfere with atomization but also can leak past plungers and barrels of close-fitting parts. The result is that the high-pressure injection system cannot deliver the correct quantity of fuel or the engine has difficulty starting in cold temperatures because not enough fuel is supplied to the combustion chamber.

Fuel density is measured with a fuel hydrometer (**FIGURE 12-29**). A fuel hydrometer will report the density in API units called the *API number*. The API is a regulatory body that develops standards for measuring fuel density. The API index corresponds to the grade of fuel and its heat content. Generally, there is a 3–5% decrease in the thermal energy content, measured using the unit Btu, of fuel for every 10-point increase in API-specific gravity.

As mentioned earlier in the chapter, determining the API index or number is important when investigating symptoms of low power or high fuel consumption. Lower specific gravity can indicate whether the fuel is blended with kerosene, Jet-A, or 1-D, which often happens in cold climates. Using heavier summer grades in cold-weather operations will often lead to fuel gelling. The API number, along with other observations about the fuel color or engine performance, will point to an incorrect grade of fuel for operating conditions. Blended fuels will have a high API number, meaning the fuel is lighter or less dense. The API number will change with the seasons and geography. For example, during the summer months in Ontario, Canada,

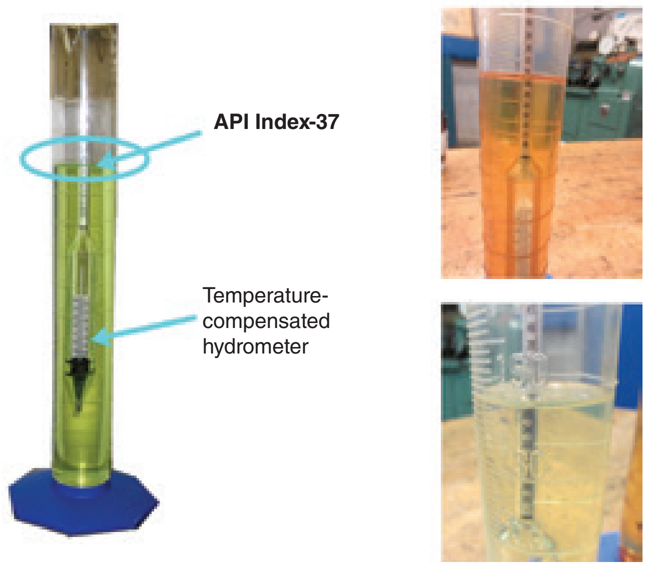

FIGURE 12-29 A temperature-compensated hydrometer measures fuel density in API units. The higher the API number, the less dense fuel is.

retailed 2-D diesel will weigh between 6.951 lb/gal (833 g/L; API 38) and 7.076 lb/gal (848 g/L; API 35). In winter the same fuel pumps will supply diesel that weighs as little as approximately 6.87 lb/gal (823 g/L; API 40).

Evaluating Fuel Quality

Diesel fuel can become stale and contaminated with water, oil, microorganisms, dirt, sediment, asphaltenes, and particles of corroded metal. If fuel has become stale and contaminated, its smell and color will change. Filters will quickly plug with contaminated fuel and overwhelm the fuel-water separator. More significantly, the ignition quality of diesel fuel will change when it becomes stale and will adversely affect engine operation. While a fuel sample can be taken and sent to a lab for analysis, technicians can quickly evaluate the quality of fuel by making some simple observations of a fuel sample in a clear container. Holding the container against a bright natural source of light allows accurate observations to be made about the color and clarity of a fuel sample taken from the fuel tank.

To evaluate fuel quality, follow the steps in **SKILL DRILL 12-2**.

Detecting Water in Diesel Fuel

A small amount of bound and free water in diesel fuel is normal. Some fuel specifications allow for up to 2.5% water contamination and some original equipment manufacturers allow 4%. However, large amounts of water in fuel tanks, lines, injectors, and filters will freeze more readily than fuel without water. Microorganisms can also grow in water in diesel fuel. Excessive injector wear, filter plugging, power loss, and corrosion of engine fuel system parts can also take place when there is too much water in diesel fuel. Injector tips can be blown off if excessive water is present in the fuel. Checking for water in diesel fuel is an important part of monitoring fuel quality at the point of supply or distribution as well as in the fuel tanks of equipment. Fuel deliveries should be checked before fuel is supplied to the engines used in mission-critical vehicles or equipment, such as backup power generators. In large fuel tanks on heavy trucks, a plug at the bottom of the fuel tank should be regularly opened, at least once a year, to drain any accumulation of water and sediment from the tank.

To detect water in diesel fuel, follow the steps in **SKILL DRILL 12-3**.

SKILL DRILL 12-2 Evaluating Fuel Quality

1. Obtain a fuel sample from the fuel tank and allow the fuel to settle in a beaker for a few minutes.
2. Place a piece of white paper behind the beaker under a natural source of light to reflect through the fuel and visually examine the fuel.
3. Record the color and clarity of the fuel. Observe any sedimentation or separation of fuel from other liquids or particles in the beaker. Fuel becomes darker as it ages. Fuel contaminated with bound water that has also gone stale turns brown. Microorganisms may even be visible in fuel.
4. Use a rapid hand motion to draw a sample of the fuel vapors toward you. Smell the vapors and note the odor of the fuel. Fuel, as it ages, will gradually lose its intense odor and begin to change, and it will have a smell similar to turpentine, varnish, plasticine, or paint. The presence of microorganisms will give the fuel a foul, rotten smell.
5. Record your observations and make a service recommendation. A fuel system with significant contamination should be drained and flushed and the filters replaced. A cetane booster may be recommended for fuel that has become slightly stale but not contaminated. Recommend a fuel stabilizer if fuel is to remain stored for several months, but do not recommend long-term storage of biodiesel.

SKILL DRILL 12-3 Detecting Water in Diesel Fuel

1. Take a fuel sample and examine it against a lighted background. Look for haziness, which indicates high amounts of bound water in fuel.
2. Using a good-quality water paste, dip the paste into a fuel sample to check for water. For vehicle fuel tanks and underground reservoirs, the paste can be applied to the end of a long dipping rod or stick. The color of the paste will change instantly when it contacts water.
3. Place a 16.9 oz (500 milliliter [mL]) sample of fuel in a clear glass beaker or jar. Slowly add 1.7–3.4 oz (50–100 mL) of methanol to the jar. Only methyl alcohol (methanol) should be used because it does not mix with diesel fuel (ethanol can be mixed with diesel fuel and will dissolve water in the fuel). The methanol will float on the diesel fuel.
4. Allow the two liquids to settle and separate.
5. Mark the container wall with a line at the point of liquid separation.
6. Vigorously shake and mix the alcohol and fuel together for 1 minute. Let the sample stand and settle for approximately 5 minutes.
7. Note the new separation line between the alcohol and the fuel and mark it with another line on the container wall.
8. Because methanol will absorb water, its volume will expand if it dissolves any water from the fuel. If water was present in the fuel sample, the line of liquid separation after mixing will be below the first marked line on the container wall. The difference between the two lines of separation is proportional to the fuel's water content. The water is now irreversibly bound with the alcohol.
9. Report your findings. If necessary, make a service recommendation to drain free water from fuel tanks.

Wrap-Up

Ready for Review

- An understanding of diesel fuel properties and characteristics, which exert a major influence on engine performance, is essential for selecting appropriate fuel and fuel additives for the wide variety of applications for diesel engines.
- Environmental considerations and legislative requirements for renewable fuels are adding complexity to today's fuel characteristics. For example, in addition to ASTM standards for diesel fuel, the EPA regulates diesel fuel to limit engine emissions, including sulfur content, aromatic content, and cetane number. Additives are tested to ensure that they have no negative health or environmental impact.
- Most countries possess their own separate and distinct performance standards for diesel fuel, but the ASTM standards for fuel are widely recognized.
- Fuels, such as diesel or gasoline, are derived from crude oil, which is a mixture of various types of hydrocarbon molecules. Through the processes of distillation and condensation, oil molecules are separated into fractions or cuts based on the boiling point temperature of each fraction.
- The performance requirements of fuels include starting ease, low wear characteristics, providing sufficient power, low-temperature operability, low combustion noise, long filter life, good fuel economy, and low emissions.
- A technician can identify the grade of diesel fuel by measuring the density of the fuel with a hydrometer, which determines its API number.
- Cetane number is one of the most significant properties of diesel fuel. This rating is a measure of the ignition quality of fuel and refers to how quickly a fuel ignites and burns.
- Biodiesel is fuel made from biological sources such as plant oil, animal fat, or a combination of petroleum-based fuel and biological fuel sources.
- The use of biodiesel offers a number of benefits both economically and environmentally, including energy security, job creation, agriculture, rural development, energy supply, and public health.
- Operationally, biodiesel performs similarly to conventional diesel in terms of power, torque, and fuel consumption without any required modifications of the fuel system.
- Biodiesel has several disadvantages, including cost, gelling of lubricating oil, poor cold-weather performance, lower power output, and reduced fuel economy.
- Because of their abundance, vegetable oils are the preferred biological source for biodiesel fuel. Oil derived from seeds or grains are the most common sources for fuel production.
- A wide variety of diesel fuel additives are used to improve the general quality and performance of diesel fuel when fuel quality is compromised. When clean, good-quality fuel is used, there is no need to introduce additives.
- Many of the claims made by additive manufacturers cannot be properly substantiated.
- The large number of available additives is grouped according to function. The four major categories include engine performance enhancers, fuel stability, fuel handling, and contaminant control.
- Determining a fuel's API index is important when investigating a low-power or high fuel consumption problem.

Key Terms

American Petroleum Institute (API) A regulatory body that develops standards for measuring fuel density.

American Petroleum Institute (API) number A measurement of a fuel's density using an API scale.

aromatic content The portion of fuel composed of a particular type of hydrocarbon molecule that is difficult to ignite and burn.

ASTM International An organization that establishes today's diesel fuel standards, formerly known as the American Society for Testing and Materials (ASTM).

auto-ignition temperature The temperature at which a fuel will ignite.

biocide A fuel treatment that kills microorganisms.

cetane booster An additive that is marketed to reduce combustion noise and smoke, improve startability in cold weather, and increase acceleration response; also known as an *ignition accelerator*.

cetane number (CN) A measure of the ignition quality of fuel; also known as *cetane rating* or *cetane value*.

cloud point The temperature at which the wax in diesel fuel begins to congeal.

distillation The process of boiling petroleum oil to separate oil molecules into fractions or cuts based on the boiling point temperature of each fraction.

Energy Independence and Security Act (EISA) Legislation that requires the increased use of renewable fuels.

ethanol Alcohol-based fuel made from starches and sugars.

fatty acid methyl ester (FAME) fuel A biodiesel produced through transesterification.

Fischer-Tropsch reaction A process used to create synthetic liquid diesel fuel from vaporized hydrocarbons.

flash point The temperature to which a fuel must be heated in order to produce a vapor that will ignite when exposed to a spark or open flame.

fractions The classification or distinction between different types, sizes, and weights of hydrocarbon molecules that make up a barrel of oil.

fuel hydrometer A tool used to measure fuel density and identify its API number.

gas-to-liquid (GTL) fuel Fuel derived from using the Fischer-Tropsch reaction.

low-sulfur diesel (LSD) Diesel fuel with a maximum sulfur content of 0.05% mass or 500 ppm.

lubricity A fuel's lubricating quality.

methanol A type of alcohol made from wood or cellulose and used as a fuel or a fuel additive.

middle distillates A fraction or cut produced in the distillation process, such as jet fuel or diesel.

octane number A measurement of the ignition characteristics of gasoline.

petroleum distillates Fuel produced from distilling crude oil.

pour point The temperature at which fuel will no longer flow through lines and filters because of wax.

Renewable Fuel Standard (RFS) Part of EISA, passed in the United States in 2007, that indirectly mandates the use of B20 fuel beginning in 2011.

straight vegetable oil (SVO) Unrefined vegetable oil used as fuel made from plants such as soybeans, jatropha, and palms.

synthetic diesel fuel Fuel made through the Fischer-Tropsch reaction.

transesterification A process that replaces glycerin in vegetable oil or animal fat with alcohol molecules.

ultra-low–sulfur diesel (ULSD) Fuel that has a maximum sulfur content of 15 ppm.

viscosity A measure of a fluid's flow characteristics, or resistance to flow.

volatility The quantity of fuel that evaporates at a particular temperature.

Review Questions

1. What effect does gasoline contamination have on diesel fuel?
   a. It lowers the auto-ignition temperature of the fuel.
   b. It lowers the flash point of the fuel.
   c. It lowers the cloud point of the fuel.
   d. It shortens the ignition delay time of the fuel.
2. Diesel fuel with a CN of 50 or greater has which of the following characteristics?
   a. It is 1-D and burns quickly.
   b. It is 1-D and burns slowly.
   c. It is 2-D and burns quickly.
   d. It is 2-D and burns slowly.
3. The temperature at which wax crystals begin to form in diesel fuel is referred to as its:
   a. cloud point.
   b. pour point.
   c. cetane number.
   d. viscosity index.
4. Which of the following properties does B5 diesel fuel have?
   a. It is red and has 5% sulfur content.
   b. It has 5% animal fat.
   c. It has 5% petroleum content.
   d. It has 5% biological-based fuel content.
5. Which of the following properties of diesel fuel has the lowest temperature value?
   a. Flash point temperature
   b. Auto-ignition temperature
   c. Pour point temperature
   d. Cloud point temperature
6. Which of the following characteristics is typical of diesel fuel with a high CN?
   a. Less combustion noise
   b. Higher emissions
   c. Poor starting characteristics
   d. Higher aromatic content
7. In comparison to petroleum-based diesel fuel, which of the following advantages does biodiesel have?
   a. Lower NOx emissions levels
   b. Higher heat content
   c. Lower pour and cloud points
   d. Better lubricity
8. Which grade of diesel fuel is used in on-highway diesel engines and provides the highest heat content and best fuel economy?
   a. 1-D
   b. 2-D
   c. 3-D
   d. 4-D
9. Which of the following characteristics is true regarding straight vegetable oil?
   a. It will cause corrosion of copper fuel system components.
   b. It requires heating before passing through the high-pressure injection system.
   c. It has low heat content and reduces engine power output.
   d. It will not cause coking of injector nozzles.
10. Which color is fresh, good-quality 2-D diesel fuel when it is commercially retailed?
    a. Red
    b. Clear
    c. Blue
    d. Dark green

ASE Technician A/Technician B Style Questions

1. Technician A says that SVO can be burned in a diesel engine without causing any long-term problems for engine durability. Technician B says that SVO will damage injectors. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
2. Technician A says that adding alcohol to diesel fuel is a good practice because it keeps fuel from waxing when it is cold and improves engine starting. Technician B says that wax in fuel should be removed at the refinery because it causes low-power complaints in hot weather. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B

3. Technician A says that adding a little gasoline to diesel fuel will help a diesel engine start faster in cold weather, reduce combustion noise, and improve power output. Technician B says that adding gasoline to diesel fuel will make starting worse, increase combustion noise, and accelerate fuel system wear. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
4. Technician A says that 2-D fuel provides the most power and best fuel economy for an on-highway diesel engine. Technician B says that 1-D is the best fuel for producing power and good fuel economy. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
5. Technician A says that 4-D fuel should not be used in on-highway diesel engines. Technician B says that 3-D is recommended for marine diesel engines. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
6. Technician A says that diesel fuel's low volatility is why so many diesel fuel pump islands appear to have a lot of spilled fuel. Technician B says that fuel spills at diesel pump islands are more common than those at gasoline pumps because truck drivers are careless when refueling. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
7. Technician A says that winter grades of diesel fuel are more likely to produce a low-power complaint because winter fuel has a lower Btu content than fuel retailed during the summer months. Technician B says that winter fuel blends will plug fuel filters easier than fuel prepared for summer seasons, which explains winter fuel low-power complaints. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
8. Technician A says that microorganisms that grow in diesel fuel and plug filters feed on fuel molecules. Technician B says that the microorganisms grow in water contained in diesel fuel. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
9. Technician A says that the smell of diesel exhaust is produced by the complete combustion of diesel fuel. Technician B says that unburned hydrocarbons produce the characteristic smell of diesel exhaust. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
10. Technician A says that thinner, low-viscosity diesel fuel will produce more power because more fuel can be injected. Technician B says that low-viscosity fuel tends to leak around plungers and barrels in high-pressure injection equipment and less fuel is injected. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B