Diesel Engine Fundamentals Part 1

Course# ME4061

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REFERENCES

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TERMINAL OBJECTIVE

1.0 Without references, **DESCRIBE** the components and theory of operation for a diesel engine.

ENABLING OBJECTIVES

1.1 **DEFINE** the following diesel engine terms:

a. Compression ratio
b. Bore
c. Stroke
d. Combustion chamber

1.2 Given a drawing of a diesel engine, **IDENTIFY** the following:

a. Piston/rod
b. Cylinder
c. Blower
d. Crankshaft
e. Intake ports or valve(s)
f. Exhaust ports or valve(s)
g. Fuel injector

1.3 **EXPLAIN** how a diesel engine converts the chemical energy stored in the diesel fuel into mechanical energy.

1.4 **EXPLAIN** how the ignition process occurs in a diesel engine.

1.5 **EXPLAIN** the operation of a 4-cycle diesel engine to include when the following events occur during a cycle:

a. Intake
b. Exhaust
c. Fuel injection
d. Compression
e. Power

ENABLING OBJECTIVES (Cont.)

1.6 **EXPLAIN** the operation of a 2-cycle diesel engine, including when the following events occur during a cycle:

a. Intake
b. Exhaust
c. Fuel injection
d. Compression
e. Power

1.7 **DESCRIBE** how the mechanical-hydraulic governor on a diesel engine controls engine speed.

1.8 **LIST** five protective alarms usually found on mid-sized and larger diesel engines.

DIESEL ENGINES

One of the most common prime movers is the diesel engine. Before gaining an understanding of how the engine operates a basic understanding of the engine's components must be gained. This chapter reviews the major components of a generic diesel engine.

EO 1.1 DEFINE the following diesel engine terms:

a. Compression ratio
b. Bore
c. Stroke
d. Combustion chamber

EO 1.2 Given a drawing of a diesel engine, IDENTIFY the following:

a. Piston/rod
b. Cylinder
c. Blower
d. Crankshaft
e. Intake ports or valve(s)
f. Exhaust ports or valve(s)
g. Fuel injector

Introduction

Most DOE facilities require some type of prime mover to supply mechanical power for pumping, electrical power generation, operation of heavy equipment, and to act as a backup electrical generator for emergency use during the loss of the normal power source. Although several types of prime movers are available (gasoline engines, steam and gas turbines), the diesel engine is the most commonly used. Diesel engines provide a self-reliant energy source that is available in sizes from a few horsepower to 10,000 hp. Figure 1 provides an illustration of a common skid-mounted, diesel-driven generator. Relatively speaking, diesel engines are small, inexpensive, powerful, fuel efficient, and extremely reliable if maintained properly.

Because of the widespread use of diesel engines at DOE facilities, a basic understanding of the operation of a diesel engine will help ensure they are operated and maintained properly. Due to the large variety of sizes, brands, and types of engines in service, this module is intended to provide the fundamentals and theory of operation of a diesel engine. Specific information on a particular engine should be obtained from the vendor's manual.

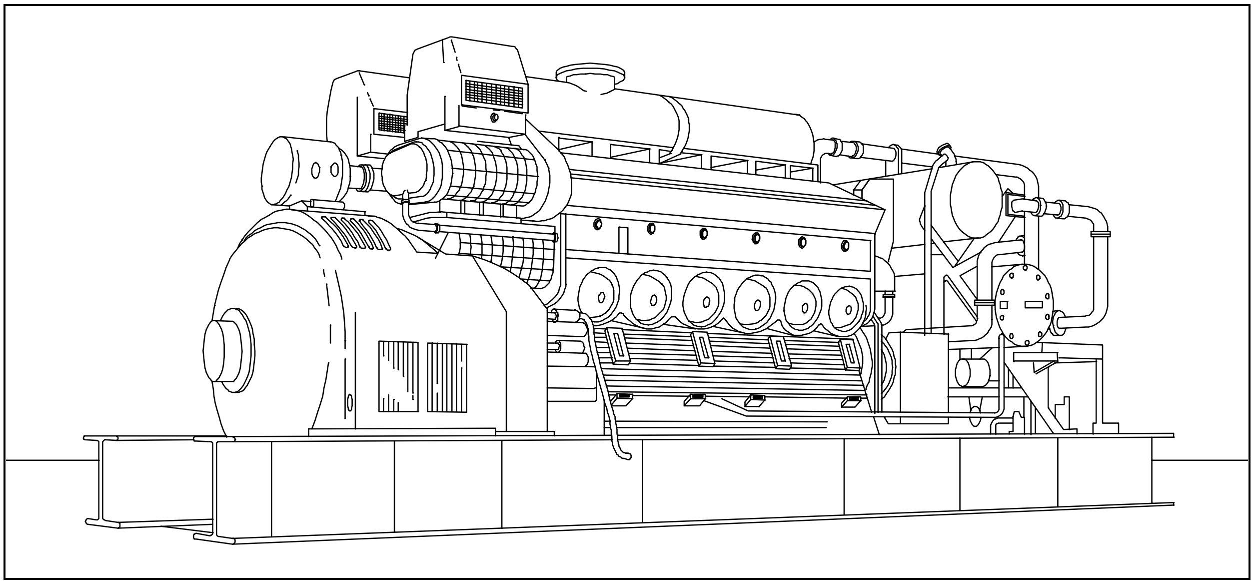

Figure 1 Example of a Large Skid-Mounted, Diesel-Driven Generator

History

The modern diesel engine came about as the result of the internal combustion principles first proposed by Sadi Carnot in the early 19th century. Dr. Rudolf Diesel applied Sadi Carnot's principles into a patented cycle or method of combustion that has become known as the "diesel" cycle. His patented engine operated when the heat generated during the compression of the air fuel charge caused ignition of the mixture, which then expanded at a constant pressure during the full power stroke of the engine.

Dr. Diesel's first engine ran on coal dust and used a compression pressure of 1500 psi to increase its theoretical efficiency. Also, his first engine did not have provisions for any type of cooling system. Consequently, between the extreme pressure and the lack of cooling, the engine exploded and almost killed its inventor. After recovering from his injuries, Diesel tried again using oil as the fuel, adding a cooling water jacket around the cylinder, and lowering the compression pressure to approximately 550 psi. This combination eventually proved successful. Production rights to the engine were sold to Adolphus Bush, who built the first diesel engines for commercial use, installing them in his St. Louis brewery to drive various pumps.

Diesel Engines

A diesel engine is similar to the gasoline engine used in most cars. Both engines are internal combustion engines, meaning they burn the fuel-air mixture within the cylinders. Both are reciprocating engines, being driven by pistons moving laterally in two directions. The majority of their parts are similar. Although a diesel engine and gasoline engine operate with similar components, a diesel engine, when compared to a gasoline engine of equal horsepower, is heavier due to stronger, heavier materials used to withstand the greater dynamic forces from the higher combustion pressures present in the diesel engine.

The greater combustion pressure is the result of the higher compression ratio used by diesel engines. The *compression ratio* is a measure of how much the engine compresses the gasses in the engine's cylinder. In a gasoline engine the compression ratio (which controls the compression temperature) is limited by the air-fuel mixture entering the cylinders. The lower ignition temperature of gasoline will cause it to ignite (burn) at a compression ratio of less than 10:1. The average car has a 7:1 compression ratio. In a diesel engine, compression ratios ranging from 14:1 to as high as 24:1 are commonly used. The higher compression ratios are possible because only air is compressed, and then the fuel is injected. This is one of the factors that allows the diesel engine to be so efficient. Compression ratio will be discussed in greater detail later in this module.

Another difference between a gasoline engine and a diesel engine is the manner in which engine speed is controlled. In any engine, speed (or power) is a direct function of the amount of fuel burned in the cylinders. Gasoline engines are self-speed-limiting, due to the method the engine uses to control the amount of air entering the engine. Engine speed is indirectly controlled by the butterfly valve in the carburetor. The butterfly valve in a carburetor limits the amount of air entering the engine. In a carburetor, the rate of air flow dictates the amount of gasoline that will be mixed with the air. Limiting the amount of air entering the engine limits the amount of fuel entering the engine, and, therefore, limits the speed of the engine. By limiting the amount of air entering the engine, adding more fuel does not increase engine speed beyond the point where the fuel burns 100% of the available air (oxygen).

Diesel engines are not self-speed-limiting because the air (oxygen) entering the engine is always the maximum amount. Therefore, the engine speed is limited solely by the amount of fuel injected into the engine cylinders. Therefore, the engine always has sufficient oxygen to burn and the engine will attempt to accelerate to meet the new fuel injection rate. Because of this, a manual fuel control is not possible because these engines, in an unloaded condition, can accelerate at a rate of more than 2000 revolutions per second. Diesel engines require a speed limiter, commonly called the governor, to control the amount of fuel being injected into the engine.

Unlike a gasoline engine, a diesel engine does not require an ignition system because in a diesel engine the fuel is injected into the cylinder as the piston comes to the top of its compression stroke. When fuel is injected, it vaporizes and ignites due to the heat created by the compression of the air in the cylinder.

Major Components of a Diesel Engine

To understand how a diesel engine operates, an understanding of the major components and how they work together is necessary. Figure 2 is an example of a medium-sized, four-stroke, supercharged, diesel engine with inlet ports and exhaust valves. Figure 3 provides a cross section of a similarly sized V-type diesel engine.

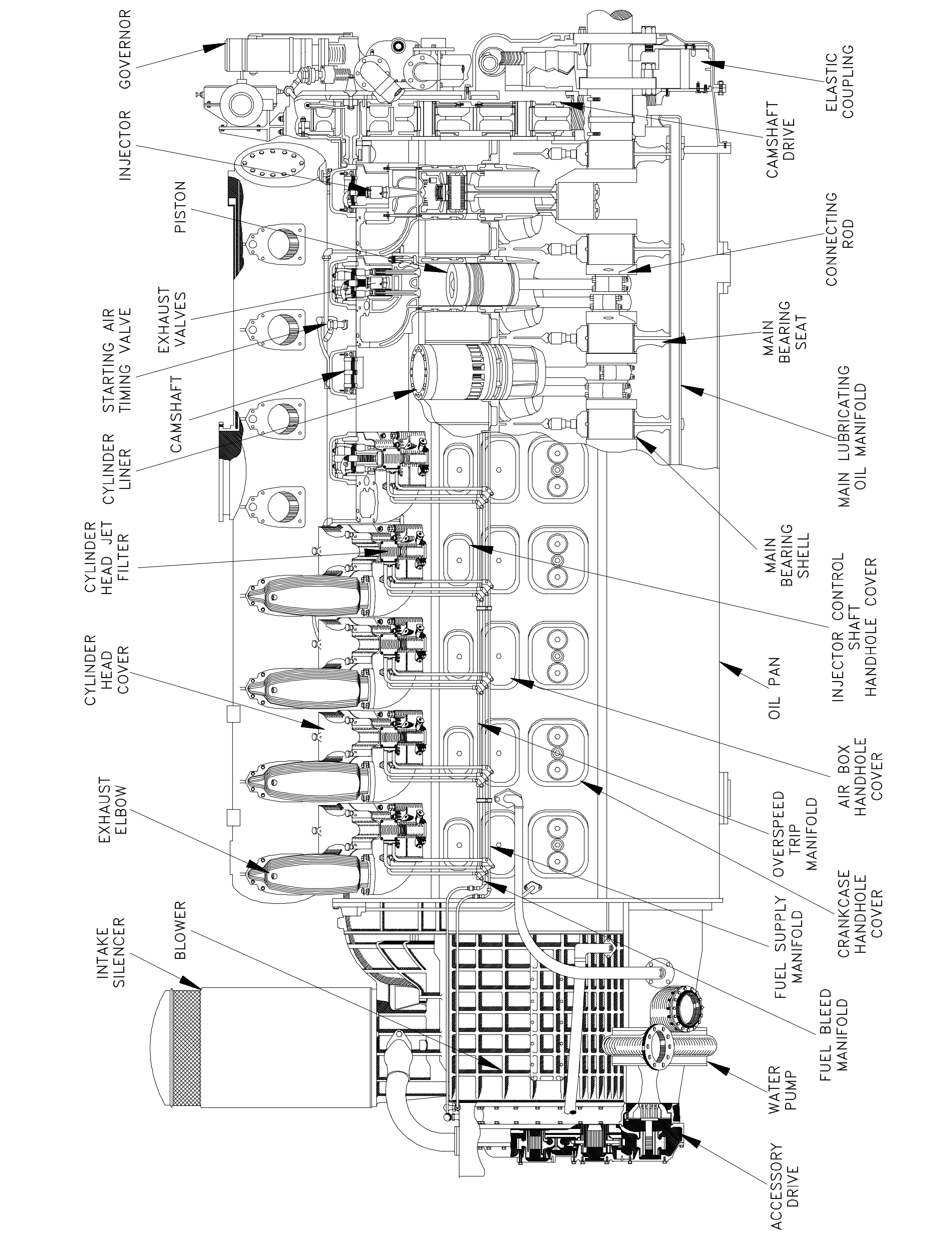

Figure 2 Cutaway of a GM V-16 Four-Stroke Supercharged Diesel Engine

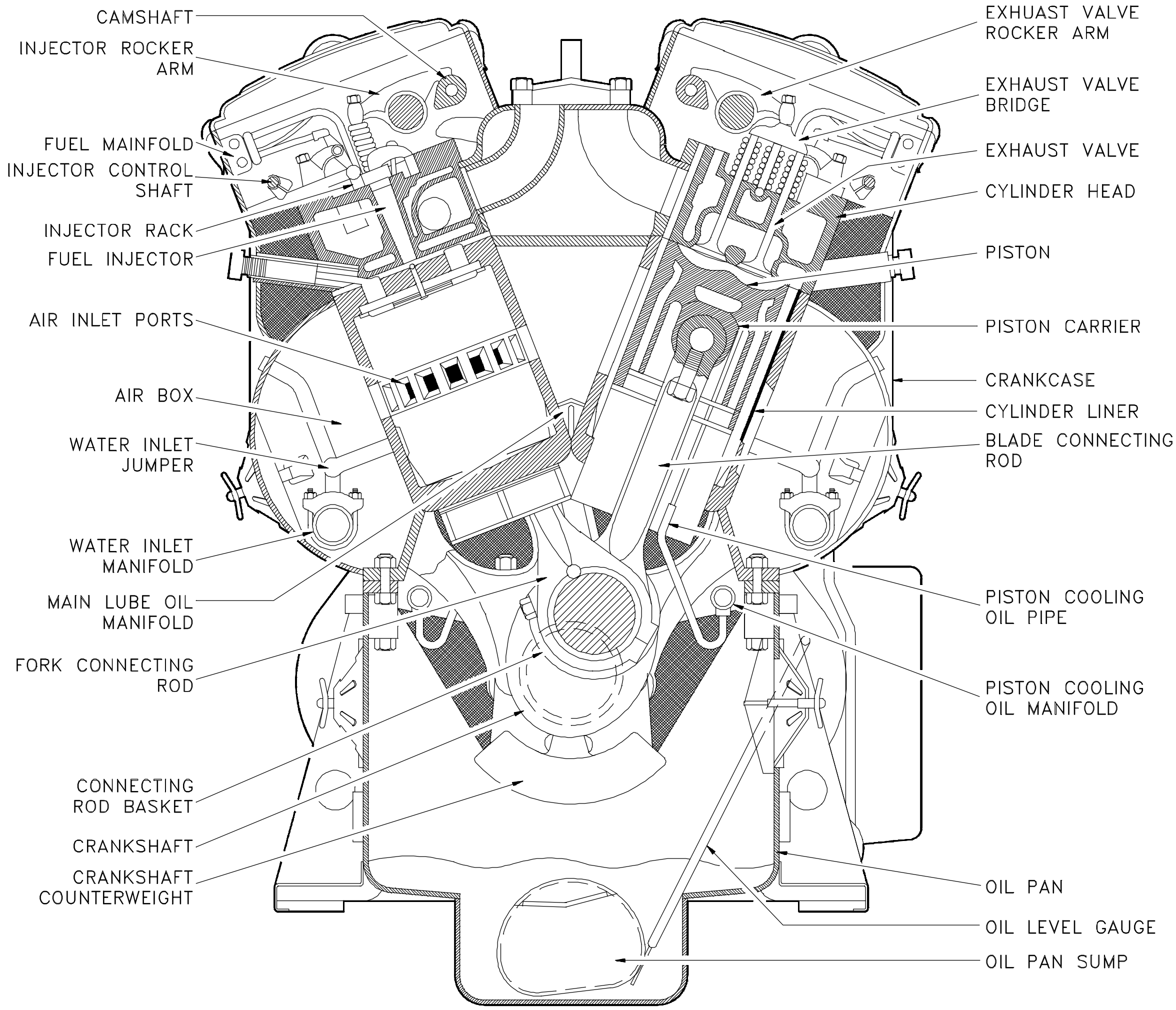

Figure 3 Cross Section of a V-type Four Stroke Diesel Engine

The Cylinder Block

The cylinder block, as shown in Figure 4, is generally a single unit made from cast iron. In a liquid-cooled diesel, the block also provides the structure and rigid frame for the engine's cylinders, water coolant and oil passages, and support for the crankshaft and camshaft bearings.

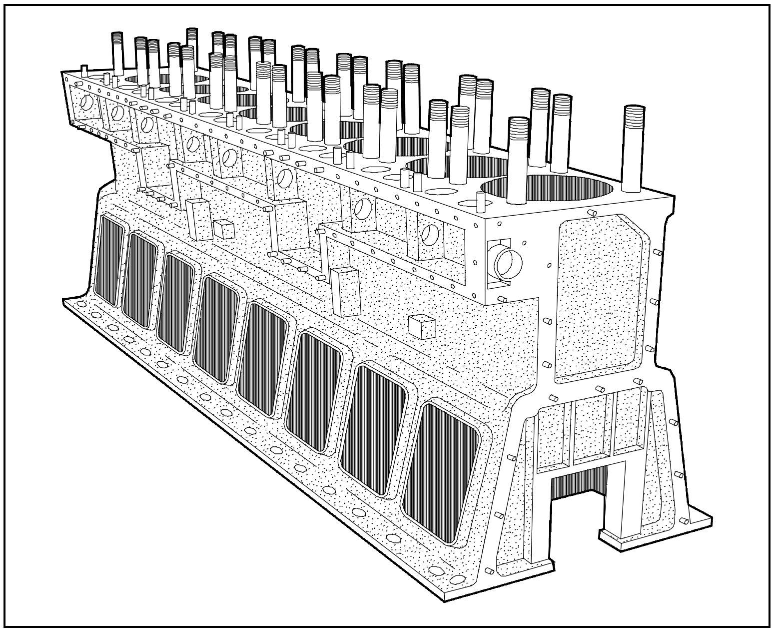

Figure 4 The Cylinder Block

Crankcase and Oil Pan

The *crankcase* is usually located on the bottom of the cylinder block. The crankcase is defined as the area around the crankshaft and crankshaft bearings. This area encloses the rotating crankshaft and crankshaft counter weights and directs returning oil into the oil pan. The oil pan is located at the bottom of the crankcase as shown in Figure 2 and Figure 3. The *oil pan* collects and stores the engine's supply of lubricating oil. Large diesel engines may have the oil pan divided into several separate pans.

Cylinder Sleeve or Bore

Diesel engines use one of two types of cylinders. In one type, each cylinder is simply machined or bored into the block casting, making the block and cylinders an integral part. In the second type, a machined steel sleeve is pressed into the block casting to form the cylinder. Figure 2 and Figure 3 provide examples of sleeved diesel engines. With either method, the *cylinder sleeve* or *bore* provides the engine with the cylindrical structure needed to confine the combustion gasses and to act as a guide for the engine's pistons.

In engines using sleeves, there are two types of sleeves, wet and dry. A dry sleeve is surrounded by the metal of the block and does not come in direct contact with the engine's coolant (water). A wet sleeve comes in direct contact with the engine's coolant. Figure 5 provides an example of a wet sleeve. The volume enclosed by the sleeve or bore is called the combustion chamber and is the space where the fuel is burned.

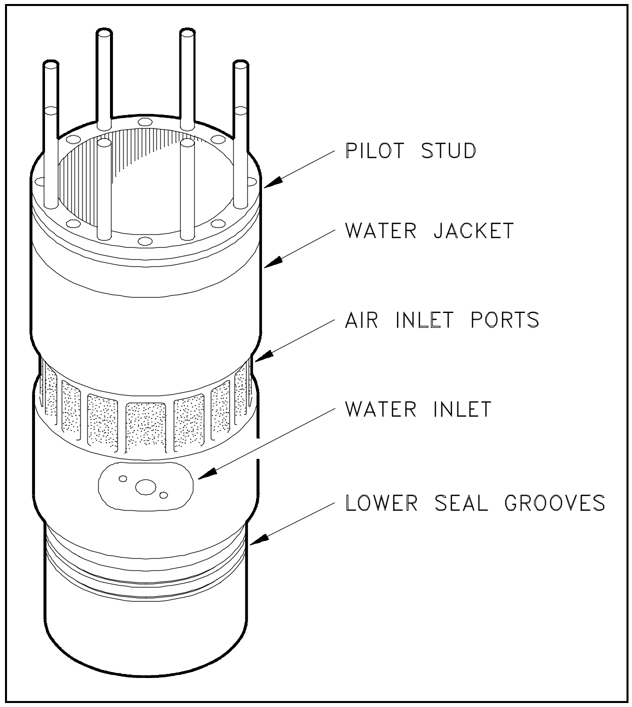

Figure 5 Diesel Engine Wet Cylinder Sleeve

In either type of cylinder, sleeved or bored, the diameter of the cylinder is called the bore of the engine and is stated in inches. For example, the bore of a 350 cubic inch Chevrolet gasoline engine is 4 inches.

Most diesel engines are multi-cylinder engines and typically have their cylinders arranged in one of two ways, an in-line or a "V", although other combinations exits. In an in-line engine, as the name indicates, all the cylinders are in a row. In a "V" type engine the cylinders are arranged in two rows of cylinders set at an angle to each other that align to a common crankshaft. Each group of cylinders making up one side of the "V" is referred to as a bank of cylinders.

Piston and Piston Rings

The *piston* transforms the energy of the expanding gasses into mechanical energy. The piston rides in the cylinder liner or sleeve as shown in Figure 2 and Figure 3. Pistons are commonly made of aluminum or cast iron alloys.

To prevent the combustion gasses from bypassing the piston and to keep friction to a minimum, each piston has several metal rings around it, as illustrated by Figure 6.

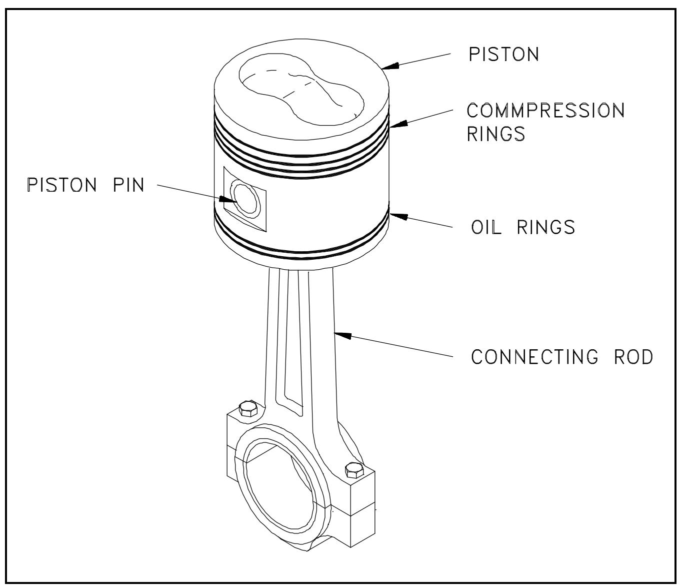

Figure 6 Piston and Piston Rod

These rings function as the seal between the piston and the cylinder wall and also act to reduce friction by minimizing the contact area between the piston and the cylinder wall. The rings are usually made of cast iron and coated with chrome or molybdenum. Most diesel engine pistons have several rings, usually 2 to 5, with each ring performing a distinct function. The top ring(s) acts primarily as the pressure seal. The intermediate ring(s) acts as a wiper ring to remove and control the amount of oil film on the cylinder walls. The bottom ring(s) is an oiler ring and ensures that a supply of lubricating oil is evenly deposited on the cylinder walls.

Connecting Rod

The *connecting rod* connects the piston to the crankshaft. See Figure 2 and Figure 3 for the location of the connecting rods in an engine. The rods are made from drop-forged, heat-treated steel to provide the required strength. Each end of the rod is bored, with the smaller top bore connecting to the piston pin (wrist pin) in the piston as shown in Figure 6. The large bore end of the rod is split in half and bolted to allow the rod to be attached to the crankshaft. Some diesel engine connecting rods are drilled down the center to allow oil to travel up from the crankshaft and into the piston pin and piston for lubrication.

A variation found in V-type engines that affects the connecting rods is to position the cylinders in the left and right banks directly opposite each other instead of staggered (most common configuration). This arrangement requires that the connecting rods of two opposing cylinders share the same main journal bearing on the crankshaft. To allow this configuration, one of the connecting rods must be split or forked around the other.

Crankshaft

The *crankshaft* transforms the linear motion of the pistons into a rotational motion that is transmited to the load. Crankshafts are made of forged steel. The forged crankshaft is machined to produce the crankshaft bearing and connecting rod bearing surfaces. The rod bearings are eccentric, or offset, from the center of the crankshaft as illustrated in Figure 7. This offset converts the reciprocating (up and down) motion of the piston into the rotary motion of the crankshaft. The amount of offset determines the stroke (distance the piston travels) of the engine (discussed later).

The crankshaft does not ride directly on the cast iron block crankshaft supports, but rides on special bearing material as shown in Figure 7. The connecting rods also have bearings inserted between the crankshaft and the connecting rods. The bearing material is a soft alloy of metals that provides a replaceable wear surface and prevents galling between two similar metals (i.e., crankshaft and connecting rod). Each bearing is split into halves to allow assembly of the engine. The crankshaft is drilled with oil passages that allow the engine to feed oil to each of the crankshaft bearings and connection rod bearings and up into the connecting rod itself.

The crankshaft has large weights, called counter weights, that balance the weight of the connecting rods. These weights ensure an even (balance) force during the rotation of the moving parts.

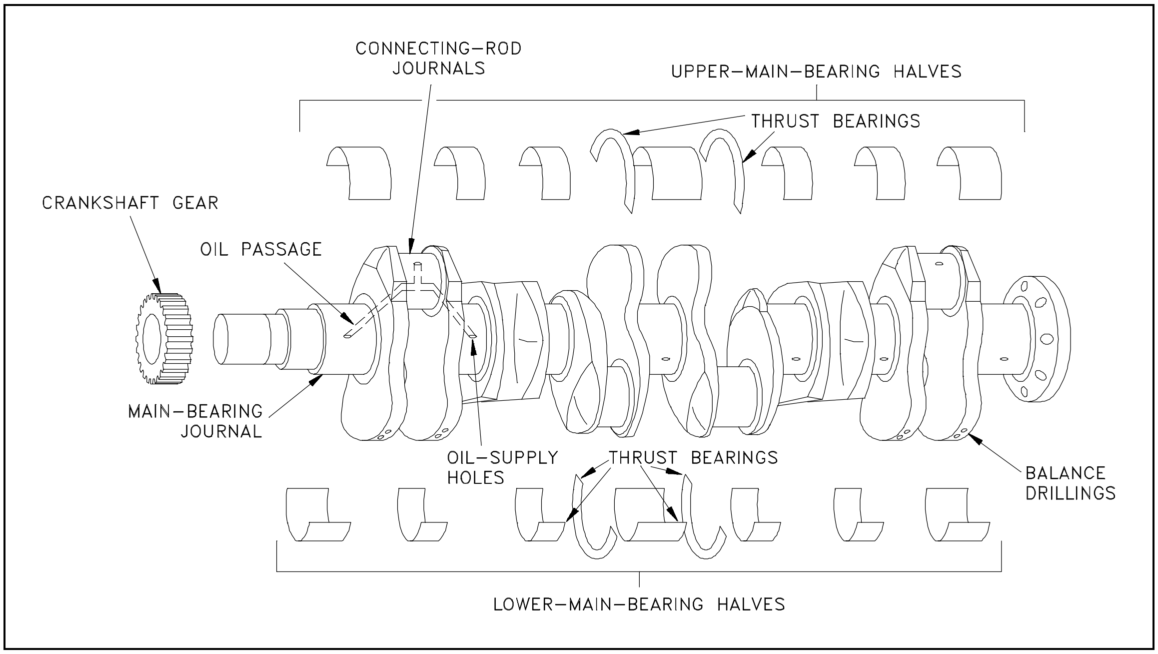

Figure 7 Diesel Engine Crankshaft and Bearings

Flywheel

The *flywheel* is located on one end of the crankshaft and serves three purposes. First, through its inertia, it reduces vibration by smoothing out the power stroke as each cylinder fires. Second, it is the mounting surface used to bolt the engine up to its load. Third, on some diesels, the flywheel has gear teeth around its perimeter that allow the starting motors to engage and crank the diesel.

Cylinder Heads and Valves

A diesel engine's *cylinder heads* perform several functions. First, they provide the top seal for the cylinder bore or sleeve. Second, they provide the structure holding exhaust valves (and intake valves where applicable), the fuel injector, and necessary linkages. A diesel engine's heads are manufactured in one of two ways. In one method, each cylinder has its own head casting, which is bolted to the block. This method is used primarily on the larger diesel engines. In the second method, which is used on smaller engines, the engine's head is cast as one piece (multi-cylinder head).

Diesel engines have two methods of admitting and exhausting gasses from the cylinder. They can use either ports or valves or a combination of both. *Ports* are slots in the cylinder walls located in the lower 1/3 of the bore. See Figure 2 and Figure 3 for examples of intake ports, and note their relative location with respect to the rest of the engine. When the piston travels below the level of the ports, the ports are "opened" and fresh air or exhaust gasses are able to enter or leave, depending on the type of port.

The ports are then "closed" when the piston travels back above the level of the ports. *Valves* (refer to figure 8) are mechanically opened and closed to admit or exhaust the gasses as needed. The valves are located in the head casting of the engine. The point at which the valve seals against the head is called the *valve seat*. Most medium-sized diesels have either intake ports or exhaust valves or both intake and exhaust valves.

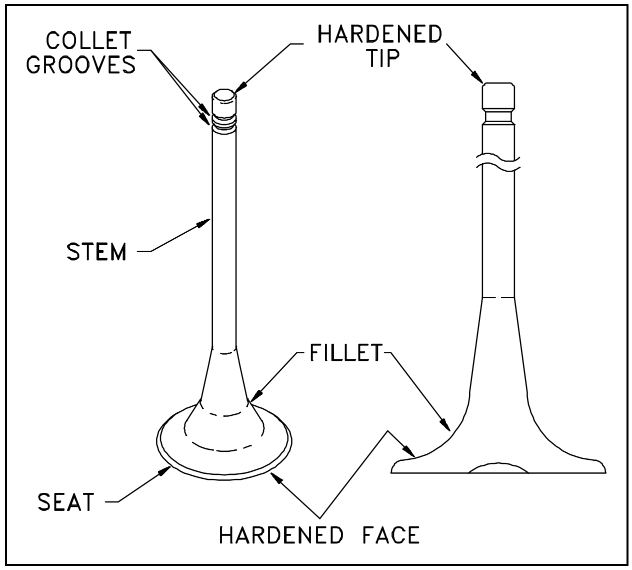

Figure 8 Diesel Engine Valve

Timing Gears, Camshaft, and Valve Mechanism

In order for a diesel engine to operate, all of its components must perform their functions at very precise intervals in relation to the motion of the piston. To accomplish this, a component called a *camshaft* is used. Figure 9 illustrates a camshaft and camshaft drive gear. Figure 2 and Figure 3 illustrate the location of a camshaft in a large overhead cam diesel engine.

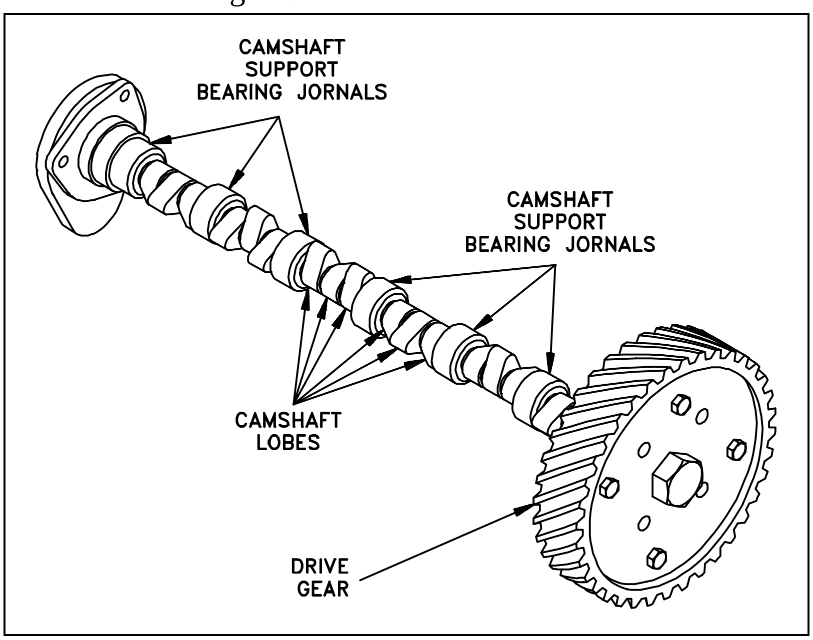

Figure 9 Diesel Engine Camshaft and Drive Gear

A camshaft is a long bar with egg-shaped eccentric lobes, one lobe for each valve and fuel injector (discussed later). Each lobe has a follower as shown on Figure 10. As the camshaft is rotated, the follower is forced up and down as it follows the profile of the cam lobe. The followers are connected to the engine's valves and fuel injectors through various types of linkages called *pushrods* and *rocker arms*. The pushrods and rocker arms transfer the reciprocating motion generated by the camshaft lobes to the valves and injectors, opening and closing them as needed. The valves are maintained closed by springs.

As the valve is opened by the camshaft, it compresses the valve spring. The energy stored in the valve spring is then used to close the valve as the camshaft lobe rotates out from under the follower. Because an engine experiences fairly large changes in temperature (e.g., ambient to a normal running temperature of about 190°F), its components must be designed to allow for thermal expansion. Therefore, the valves, valve pushrods, and rocker arms must have some method of allowing for the expansion. This is accomplished by the use of valve lash. *Valve lash* is the term given to the "slop" or "give" in the valve train before the cam actually starts to open the valve.

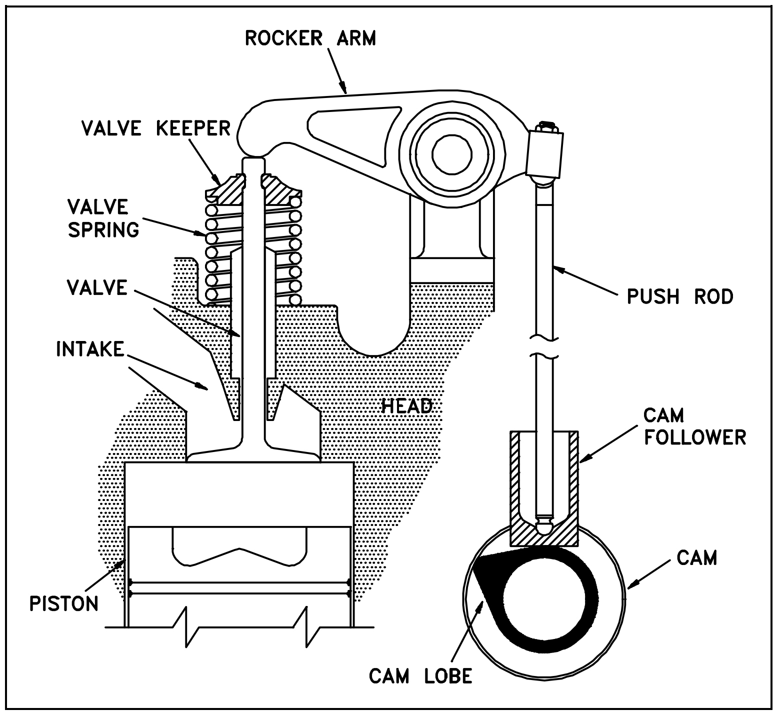

Figure 10 Diesel Engine Valve Train

The camshaft is driven by the engine's crankshaft through a series of gears called idler gears and timing gears. The gears allow the rotation of the camshaft to correspond or be in time with, the rotation of the crankshaft and thereby allows the valve opening, valve closing, and injection of fuel to be timed to occur at precise intervals in the piston's travel. To increase the flexibility in timing the valve opening, valve closing, and injection of fuel, and to increase power or to reduce cost, an engine may have one or more camshafts. Typically, in a medium to large V-type engine, each bank will have one or more camshafts per head. In the larger engines, the intake valves, exhaust valves, and fuel injectors may share a common camshaft or have independent camshafts.

Depending on the type and make of the engine, the location of the camshaft or shafts varies. The camshaft(s) in an in-line engine is usually found either in the head of the engine or in the top of the block running down one side of the cylinder bank. Figure 10 provides an example of an engine with the camshaft located on the side of the engine. Figure 3 provides an example of an overhead cam arrangement as on a V-type engine. On small or mid-sized V-type engines, the camshaft is usually located in the block at the center of the "V" between the two banks of cylinders. In larger or multi-camshafted V-type engines, the camshafts are usually located in the heads.

Blower

The diesel engine's *blower* is part of the air intake system and serves to compress the incoming fresh air for delivery to the cylinders for combustion. The location of the blower is shown on Figure 2. The blower can be part of either a turbocharged or supercharged air intake system. Additional information on these two types of blowers is provided later in this module.

Diesel Engine Support Systems

A diesel engine requires five supporting systems in order to operate: cooling, lubrication, fuel injection, air intake, and exhaust. Depending on the size, power, and application of the diesel, these systems vary in size and complexity.

Engine Cooling

Nearly all diesel engines rely on a liquid cooling system to transfer waste heat out of the block and internals as shown in Figure 11. The cooling system consists of a closed loop similar to that of a car engine and contains the following major components: water pump, radiator or heat exchanger, water jacket (which consists of coolant passages in the block and heads), and a thermostat.

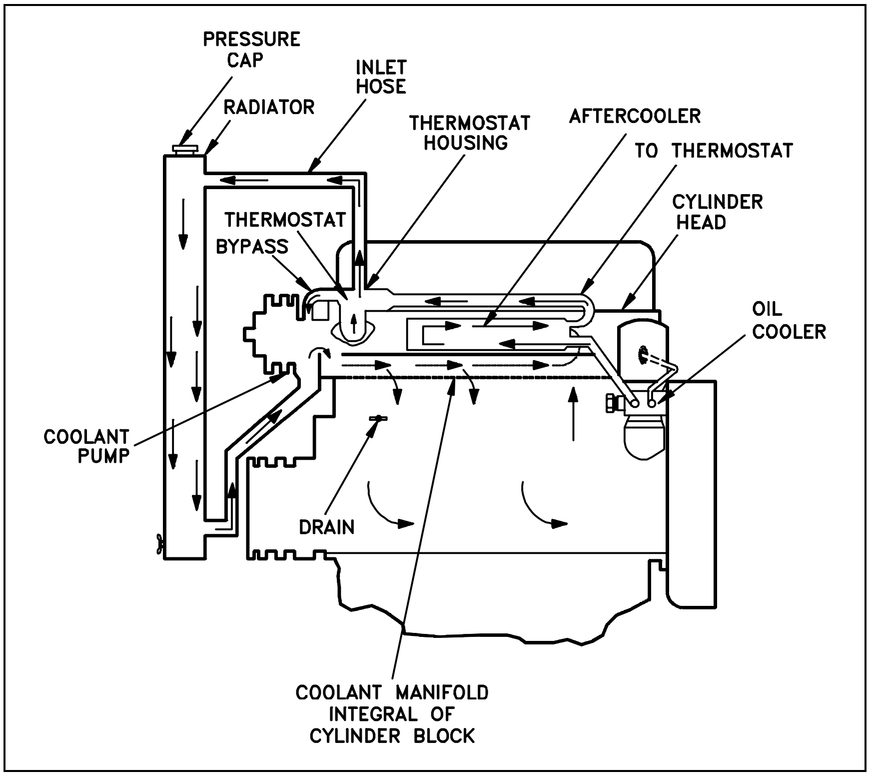

Figure 11 Diesel Engine Cooling System

Engine Lubrication

An internal combustion engine would not run for even a few minutes if the moving parts were allowed to make metal-to-metal contact. The heat generated due to the tremendous amounts of friction would melt the metals, leading to the destruction of the engine. To prevent this, all moving parts ride on a thin film of oil that is pumped between all the moving parts of the engine.

Once between the moving parts, the oil serves two purposes. One purpose is to lubricate the bearing surfaces. The other purpose is to cool the bearings by absorbing the friction-generated heat. The flow of oil to the moving parts is accomplished by the engine's internal lubricating system.

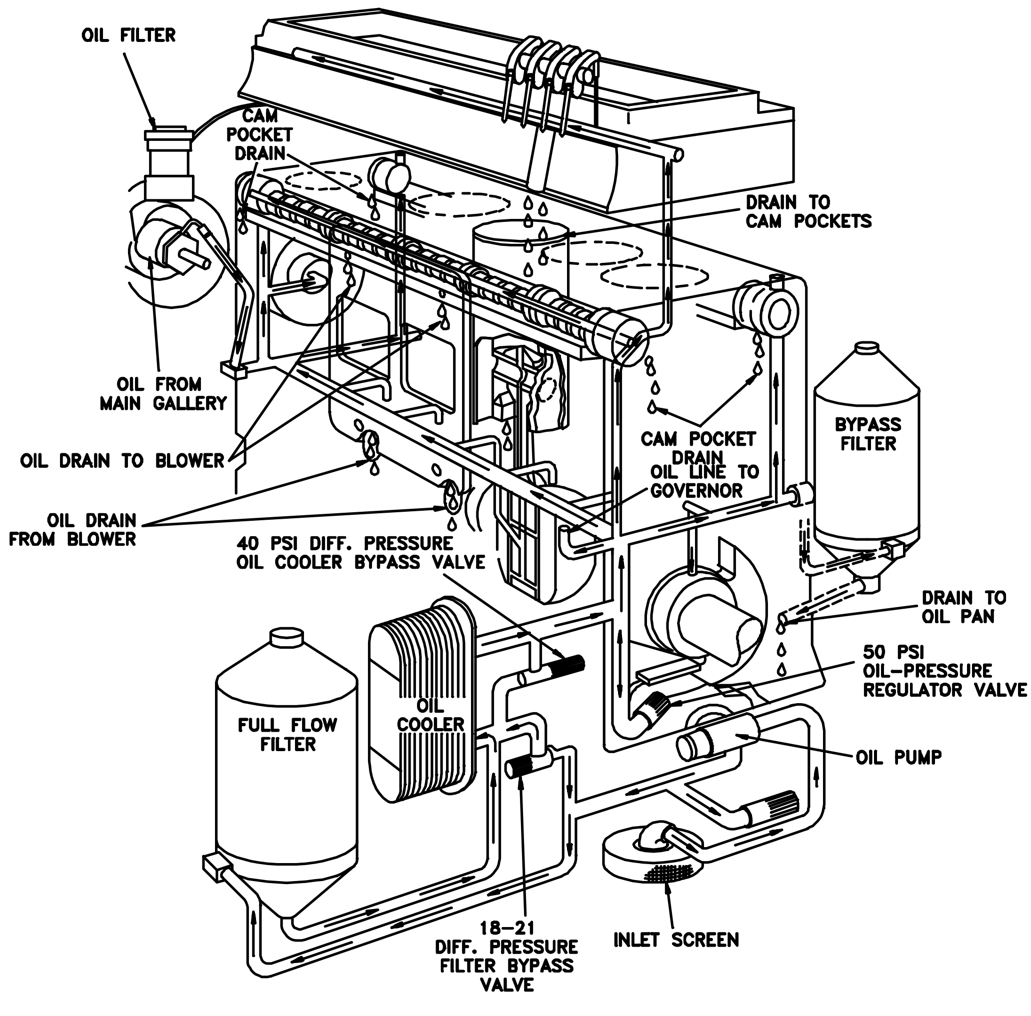

Figure 12 Diesel Engine Internal Lubrication System

Oil is accumulated and stored in the engine's oil pan where one or more oil pumps take a suction and pump the oil through one or more oil filters as shown in Figure 12. The filters clean the oil and remove any metal that the oil has picked up due to wear. The cleaned oil then flows up into the engine's oil galleries. A pressure relief valve(s) maintains oil pressure in the galleries and returns oil to the oil pan upon high pressure. The oil galleries distribute the oil to all the bearing surfaces in the engine.

Once the oil has cooled and lubricated the bearing surfaces, it flows out of the bearing and gravity-flows back into the oil pan. In medium to large diesel engines, the oil is also cooled before being distributed into the block. This is accomplished by either an internal or external oil cooler. The lubrication system also supplies oil to the engine's governor, which is discussed later in this module.

Fuel System

All diesel engines require a method to store and deliver fuel to the engine. Because diesel engines rely on injectors which are precision components with extremely tight tolerances and very small injection hole(s), the fuel delivered to the engine must be extremely clean and free of contaminants.

The fuel system must, therefore, not only deliver the fuel but also ensure its cleanliness. This is usually accomplished through a series of in-line filters. Commonly, the fuel will be filtered once outside the engine and then the fuel will pass through at least one more filter internal to the engine, usually located in the fuel line at each fuel injector.

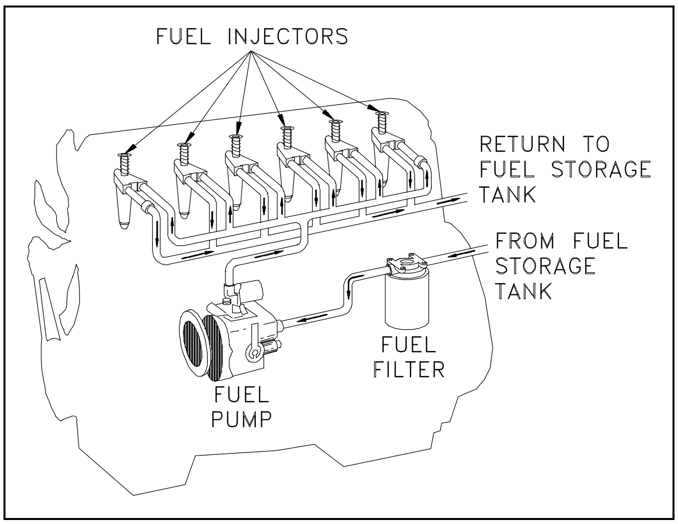

Figure 13 Diesel Engine Fuel Flowpath

In a diesel engine, the fuel system is much more complex than the fuel system on a simple gasoline engine because the fuel serves two purposes. One purpose is obviously to supply the fuel to run the engine; the other is to act as a coolant to the injectors. To meet this second purpose, diesel fuel is kept continuously flowing through the engine's fuel system at a flow rate much higher than required to simply run the engine, an example of a fuel flowpath is shown in Figure 13. The excess fuel is routed back to the fuel pump or the fuel storage tank depending on the application.

Air Intake System

Because a diesel engine requires close tolerances to achieve its compression ratio, and because most diesel engines are either turbocharged or supercharged, the air entering the engine must be clean, free of debris, and as cool as possible. Turbocharging and supercharging are discussed in more detail later in this chapter. Also, to improve a turbocharged or supercharged engine's efficiency, the compressed air must be cooled after being compressed. The air intake system is designed to perform these tasks.

Air intake systems vary greatly from vendor to vendor but are usually one of two types, wet or dry. In a wet filter intake system, as shown in Figure 14, the air is sucked or bubbled through a housing that holds a bath of oil such that the dirt in the air is removed by the oil in the filter. The air then flows through a screen-type material to ensure any entrained oil is removed from the air. In a dry filter system, paper, cloth, or a metal screen material is used to catch and trap dirt before it enters the engine (similar to the type used in automobile engines).

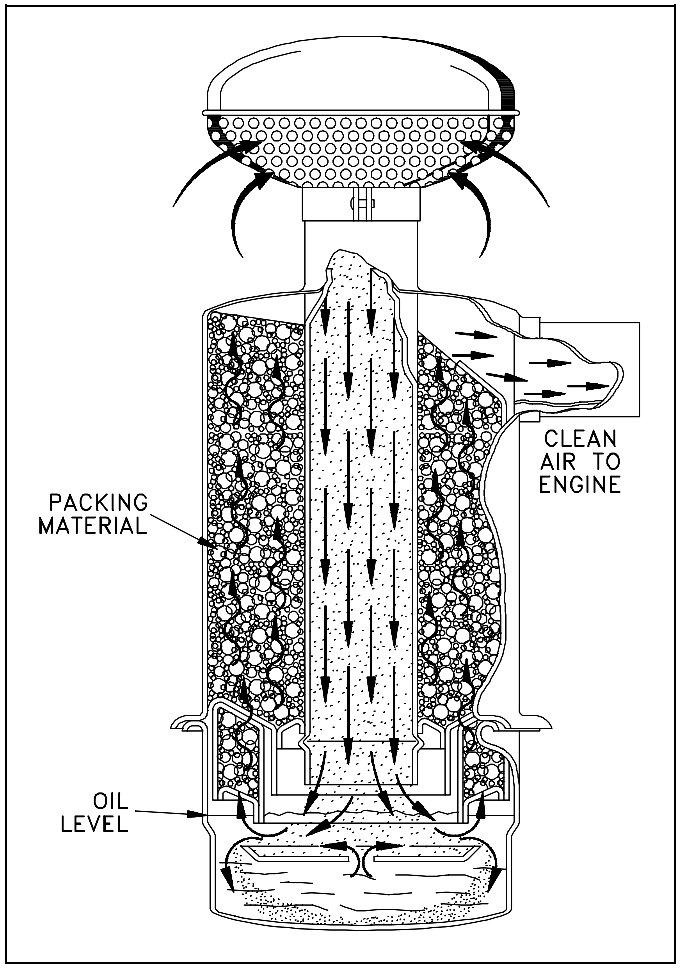

Figure 14 Oil Bath Air Filter

In addition to cleaning the air, the intake system is usually designed to intake fresh air from as far away from the engine as practicable, usually just outside of the engine's building or enclosure. This provides the engine with a supply of air that has not been heated by the engine's own waste heat.

The reason for ensuring that an engine's air supply is as cool as possible is that cool air is more dense than hot air. This means that, per unit volume, cool air has more oxygen than hot air. Thus, cool air provides more oxygen per cylinder charge than less dense, hot air. More oxygen means a more efficient fuel burn and more power.