DIESEL ENGINE FUNDAMENTALS

A diesel engine is an internal combustion reciprocating piston engine that operates on liquid fuel. It converts the chemical energy of the fuel, through timed explosions, into mechanical power. This event occurs in a combustion chamber or a "cylinder." Almost all diesel engines have more than one cylinder. These multiple cylinders are most often arranged in-line, or in a V-type configuration. Each cylinder of the typical diesel engine has a "piston" that reciprocates (moves up and down) within the cylinder. Each piston is connected to the "crankshaft" by means of a link known as a "connecting rod." The "crankshaft" is the main shaft of the engine, which together with the connecting rods, changes reciprocating motion of the pistons to rotary motion. The diesel engine is also known as a compression ignition engine, to distinguish it from the gasoline engine which uses a spark to ignite the air-fuel mixture.

Arrangement of cylinders:

Engine Operating Sequence

For internal combustion engines to operate, there is a definite series of events that must occur in sequence:
— Intake: Fill cylinder with air (diesel) or air-fuel mixture (gasoline).
— Compression: Compress air (diesel) or air-fuel mixture (gasoline).
— Power: Create and utilize explosive force for power production through injection of finely atomized fuel into cylinder at high pressure (diesel) or spark ignition of air-fuel mixture (gasoline).
— Exhaust: Remove burned mixture from cylinder.

This series of events must be repeated over and over in the same sequence, in each cylinder if the engine is to run. Relating to this series of events, the only type of diesel engine currently used in Escondido is the Four-Stroke cycle engine. A cycle is a complete sequence of events, which is repeated over and over. A piston moves up and down in the cylinder. Each movement of the piston is called a stroke.

**Four-Stroke cycle diesel engine.**

— As the piston moves down from a raised position, intake valves are opened and clean air flows into the cylinder.
— On the next stroke, the piston moves upward after the intake valve is closed, compressing it into a very small space which heats the air upwards of 1,000 degrees F.
— The heat and pressure are so great that when a finely atomized mist of fuel is injected into the cylinder, a powerful explosion results. This forces the piston down creating power.
— While the piston moves back up to its original position, exhaust valves open, allowing the burned gases to exit the engine. The four-stroke cycle has been completed and the cycle is repeated. Only one stroke out of four is a power stroke. The entire combustion cycle takes two revolutions of the crankshaft or four strokes.

**Note:** In Escondido apparatus have in line 6 cylinders. All are turbo charged and after cooled.
Advantages of Diesels

The diesel engine offers a number of advantages over gasoline engines for certain applications. These include:

- Higher reliability in operation
- Lower fuel consumption per horsepower/hour
- Greater sustained torque
- Lower fire hazard (combustible liquid vs. flammable liquid)
- Fuel lower in the refining chain (cheaper for the oil companies, though taxed more, which equalizes the retail cost)

A well-maintained diesel engine is highly reliable. When supplied with clean fuel, it can operate continuously with little chance of breakdown. Diesel engines vs. gasoline engines of similar displacement will usually have 50 percent greater fuel efficiency. This is due to two main factors:

- More energy per gallon of fuel
  - Diesel 139,500 BTU's per gallon
  - Gasoline 124,500 BTU's per gallon
- Leaner air-fuel mixture
  - Diesel maximum of 40:1
  - Gasoline maximum of 18:1

Engine Size

Displacement of an engine is a measurement of its size. It is equal to the number of cubic inches the piston displaces as it moves from bottom dead center (BDC) to top dead center (TDC). The displacement of an engine is determined by its bore, stroke, and the number of cylinders. Bore is the inside diameter of the cylinders. Stroke is the distance the piston travels from BDC to TDC. To find the overall engine displacement, you must first find the volume of a single cylinder - and then multiply that figure by the number of cylinders. To calculate, you need to know the formula for the volume of a cylinder as a geometric shape, which is \( \pi/4 \). This equals 0.7854. Multiply by the bore squared in inches x the stroke in inches x the number of cylinders. We will show an example using a 2013 Pierce Arrow XT CAT C-13 engine which is a 6-cylinder engine having a bore of 5.12" and a stroke of 6.18".

\[
\text{Displacement} = 0.7854 \times \text{bore squared} \times \text{stroke} \times \# \text{ of cylinders}
\]

\[
= 0.7854 \times 5.12" \times 6.18" \times 6
\]

\[
= 763.3 \text{ cubic inches}
\]
Certain engines have displacement and configuration information in their model number, making it even easier to figure displacement. Navistar (International Harvester) uses a different system which tells you directly. Their DTA-466 engine indicates that it is a diesel, turbocharged, after cooled, of 466 cubic inches displacement.

(Left.) The term used to indicate the diameter of an engine cylinder is the "bore."  
(Right.) Determining engine stroke.

**Compression Ratio**

Compression ratio of an engine is the extent to which the air is compressed within a cylinder. It is the relationship of the maximum volume of an engine cylinder with the piston at BDC, to the minimum volume of the cylinder at TDC. The Caterpillar C13 used in many of our structure engines has a compression ratio of 17:1. Therefore, the air in the cylinder is compressed to 1/17 its original volume. It should be noted that diesel engine compression ratios are often as high as 22 to 1 whereas gasoline engines rarely exceed 13 to 1.
Compression ratio is the relationship between the cylinder volume when the piston is at bottom dead center (left) and the cylinder volume when the piston is at top dead center (right).

**Horsepower and Torque**

Horsepower is a measurement of the ability of an engine to do work. One horsepower is defined as the ability to lift 33,000 pounds one foot in one minute. The term dates back to the 17th Century and James Watt's development of the steam engine. Watt, whose name is now the Systeme International des Unites (S.I.) term for power, first used his engine to pump water out of mines. Previously, such pumping had been done with draft horses attached to a lever that was geared to operate a pump. So potential buyers wanted to know how many horses the engine could replace. Brake horsepower (BHP) is a measurement of actual usable power delivered to the crankshaft of the engine.

Torque is the turning or twisting force on an object and is measured in pounds foot (lb. ft.). It differs from horsepower in that it may not produce motion and it is independent of time. For example, if you put 50 pounds of force on the end of a 3' lever, there would be 150 lb. ft. of torque regardless of whether or not the lever moved or for how long the force was applied.
Horsepower is derived from torque through this formula:

\[
\text{Horsepower} = \text{Revolutions per minute (RPM)} \times \frac{\text{Torque}}{5252}
\]

Diesel engines produce much more torque than gasoline engines over a narrower RPM range often resulting in similar BHP ratings. The torque is a much more important figure for moving a heavy object such as fire apparatus.

On modern engines, both horsepower and torque are measured on a device known as a dynamometer. A dynamometer includes a resistance creating device, such as a paddle wheel revolving in a fluid with a known viscosity, which absorbs and dissipates the force the engine produces. Calculations are done electronically, while gauges or readouts display the engine’s ratings.

**Cooling Systems**

Two main methods are used to cool compression ignition engines:

- Water cooling
- Air cooling

Both major methods of cooling are effective though water cooling is much more common. Air cooling is used primarily in small engines, but it has been used successfully in engines up to 400 cubic inches of displacement.

Cooling systems of some kind are necessary in any internal combustion engine. If no cooling system were provided, parts would melt from the heat of the burning fuel and pistons would expand so much they would seize. Approximately 1/3 of the fuel's heat energy is transformed into useful work. Another 1/3 goes out the exhaust pipe unused, and the remaining 1/3 must be handled by the cooling system. The heat removed from a medium duty truck engine (Brush Rig) is sufficient to keep a six-room house warm at 0 degrees F weather.

The lubricating system also contributes to the cooling of the engine. In many engines, oil coolers are provided to reduce oil temperature. Such equipment maintains better lubrication and also keeps the engine temperature within prescribed limits.

The pressurized cooling system of a water cooled engine consists of the cylinder block and head water jacket, thermostat, water pump, radiator, radiator cap, fan, fan drive belt, and necessary hoses. Control of engine temperature is regulated by the thermostat (or thermostats) which regulate the flow of coolant within the cooling system.

Air cooled engines require the constant circulation of a lot of air. This is provided by large capacity fans (belt or gear driven), together with thermostatic control. Cooling fins are
provided on the cylinders and cylinder heads. These fins increase the effective surface area for improved heat removal.

**Turbochargers**

A turbocharger is a device consisting of an exhaust gas driven turbine wheel and shaft, with a centrifugal compressor wheel connected to the opposite end of that shaft. There is also a center support housing that directs lube oil for the rotating assembly. The last two major parts are the turbine (exhaust) housing and compressor (intake) housing. The turbine housing is bolted to the outlet flange of the exhaust manifold. As the engine accelerates from idle RPM, the exhaust gases leave the cylinders and flow through the exhaust manifold into the turbine housing. This causes the turbine wheel and shaft to rotate upwards of 100,000 RPM (at peak engine speed and load). On the opposite end of the shaft, the compressor wheel rotates at the same speed, drawing in and compressing fresh air. The compressed air is then directed through the compressor housing, the intake system, and into the engine cylinders. The higher volume and density of air increases the horsepower, raises the fuel economy, and permits the cleaner burning of the fuel.

As the exhaust gases leave the cylinder they must pass through the turbine. This causes the turbine to spin. Since the shaft connects to the compressor, the compressor spins also. As the compressor spins, air is forced into the cylinder.
After Coolers

As air is compressed, its temperature rises. For most efficient combustion, the temperature must be relatively low and within certain limits. To reduce the temperature of the intake air after it has been compressed by the turbocharger, the air travels through an after cooler. By reducing the air temperature entering the engine, its density is increased so that a greater amount of oxygen by weight enters the cylinder. As a result, combustion efficiency rises (more power) without increasing fuel consumption.

The cooling of the compressed air is accomplished by coolant supplied by the engines water pump flowing through a core with fins (basically a radiator) that the air passes over. Remember that the intake air is very hot and dense after passing through a turbocharger or blower. Its ambient temperature is much greater than the coolant temperature of the engine, so it has a dramatic effect on intake air temperature and density.

Fuel Systems

The equipment used to force fuel into the combustion chamber is a critical part of the diesel engine. Diesel injection systems perform many more functions than a carburetor on a gasoline engine.

We know that a diesel engine compresses air and at the point of maximum compression, fuel is injected into the combustion chamber. Ignition takes place as a result of the high temperature of the air and proper atomization of the fuel.

The fuel is forced into the combustion chamber by hydraulic pressure on the fuel developed mechanically by the fuel pump and injector. Since high pressure exists in the combustion chamber at the time of injection, the injection system must develop pressures in excess of combustion chamber pressures. To deliver fuel to the combustion chamber, a diesel fuel injection system must fulfill five main needs:

- Meter correct quantity of fuel injected.
- Time start and finish of fuel injection correctly.
- Control rate of fuel injection.
- Atomize fuel into very fine droplets.
- Properly distribute fuel within combustion chamber.

Modern diesel engines require peak injection pressures in excess of 25,000 PSI to run cleanly and efficiently. A clean, water-free supply of fuel is critical to the durability of fuel system components. Extremely close tolerance (.0001") parts are at the heart of fuel pumps and injectors—a very small piece of dirt or grit can stop an engine completely, resulting in a large repair bill.
Diesel fuel, unlike gasoline, does not produce a strong vapor barrier. Storage in tanks, whether fixed or mobile, can be detrimental to keeping diesel free of moisture from condensation. To minimize moisture buildup, don’t let the fuel sit too long (over two months) and keep the tank filled as high as possible.

**Basic Electricity and Ohm's Law**

Currently, the electron theory is the most accepted theory of electricity. In essence, it proposes that all matter consists of molecules and that molecules are in turn made up of two or more, smaller particles called atoms. These atoms are further divided into smaller particles called protons, neutrons, and electrons.

These particles are the same in all matter whether a gas, a liquid, or a solid. The different properties or characteristics of the matter take form according to the arrangement and number of protons, neutrons, and electrons that make up the atoms.

The proton has a natural positive charge of electricity. The electron has a negative charge. The neutron has no charge at all but adds weight to the matter.

Protons and neutrons form the nucleus (central core) of the atoms about which the electrons rotate. Electrons carry small negative charges of electricity, which neutralizes the positive charge of the protons.

In most elements, the nucleus is composed of protons and neutrons, which are surrounded by closely held electrons that never leave the atom. These are called BOUND ELECTRONS. When bound electrons are in the majority in an element or compounded material, the material is called an INSULATOR or a nonconductor of electricity.

In other types of materials, the nucleus is surrounded by a group of electrons which can be freed to move from one atom to the other when electricity is applied. Electrons of this kind are known as FREE ELECTRONS, and the material made up of these atoms is called CONDUCTORS of electricity. The rate at which free electrons drift from atom to atom determines the amount of CURRENT. In order to create a drift of electrons through a circuit, it is necessary to have an electrical pressure or VOLTAGE.

**ELECTRIC CURRENT** is the flow of electrons. The more electrons in motion, the stronger the current. The greater the concentration of electrons at a battery or alternator terminal, the higher the pressure between the electrons. The greater this pressure (voltage) is, the greater the flow of electrons.

The pressure between the electrons is measured in VOLTS. The flow of electrons (current) is measured in AMPERES. One amp is an electron flow of 62.8 billion electrons past a given point in one second. Opposing the flow of electrons is the RESISTANCE of the conductors, which is measured in OHMS. Some materials offer greater resistance to
electron flow than others: iron more than copper; copper more than silver. The length of the connecting wiring also contributes to the amount of resistance in a circuit. Finally, the size of the wiring is also a resistance factor. Just like fire hose, a conductor of small diameter will offer greater resistance than a conductor of large diameter.

Ohm's Law is the mathematical relationship between voltage, resistance, and the amount of current in an electrical circuit. Each affects the other, and the relationship is stated as: 

\[ E = IR \]  
\( E = \text{voltage in volts} \) \( I = \text{current in amperes} \) \( R = \text{resistance in ohms} \). Also by taking \( E = IR \), you get \( R = E/I \), and \( I = E/R \). Ohm's Law is used extensively in checking and troubleshooting electrical circuits and components. For example, the current flowing through the coils of a 12V alternator is 3.0 amperes (amps). What is the resistance of the coils? Take \( R = E/I \) and you have \( 12/3 \) which equal 4 ohms of resistance.

Studying Ohm's Law reveals how a change in one factor affects the others. If the resistance of a circuit increases and the voltage remains constant, current will decrease. To illustrate this in real terms: If the battery cables are loose or corroded, high resistance will be caused. The result will be not enough current reaching the starting motor, lights, or other components to provide for proper operation.

**Types of Circuits and Solenoids**

There are three basic types of electrical circuits:

- Series
- Parallel
- Series-parallel

All circuits, regardless of type, consist of a source of electricity (battery or alternator), pieces of electrical equipment or devices, and electrical conductors that connect the equipment or devices to the source. In a series circuit, the current passes from the power source to each device in turn, then back to the other terminal of the battery. The current has only one path to flow. The amount of current (amps) will be the same in all parts of the circuit.

In parallel circuits, there will be more than one path. In this type of circuit, one terminal of each device is connected to a common conductor, which leads to one terminal of the battery. The remaining terminals of each device are connected to another common conductor that in turn is connected to the opposite terminal of the battery.

Series-parallel circuits are those which have some electrical devices connected in series and others in parallel.

An **electromagnet** can be described as a conductor with current flowing through it. The components of an electromagnet include a soft iron core, a number of windings, and
current flow. The factors that control the strength of an electromagnet are the number of windings and the current flow. The most common form of electromagnet is a solenoid which is a tubular coil of wire (windings) with an air core surrounding an iron core that moves when current is introduced. The current produced is used to operate some type of mechanism or switch such as a starter solenoid. The solenoid moves a starting motor drive which engages the flywheel ring gear on an engine.

**Electromagnetic induction** is defined as producing electricity with electromagnets, which is how generators and alternators function. They convert mechanical energy supplied by the engine into electrical energy to maintain the storage battery in a fully charged condition and to supply electrical power for accessory equipment. When a coil of wire is moved through a magnetic field, a voltage will be induced, or generated in the coil. Voltage can be induced in either of two ways:

- By moving a coil of wire through a magnetic field (DC generators)
- By keeping the coil stationary and moving the magnetic field (AC generators)

It should be pointed out that generators and alternators serve a similar purpose, but as listed above, they do it in different ways. Alternators create AC current so they must convert it back to DC through the use of rectifiers or diodes which will limit the current flow to just one direction on the output end.

Another important electrical system component is the voltage regulator. The regulator is an automatic switch that controls charging system output so voltage and current will not exceed predetermined values. Regulation is needed so excessive voltage will not damage batteries or other electrical system components.

**Power Train**

The group of components that are used to transmit power from the engine to the drive wheels is known as the power train. This group consists of the clutch, transmission, u-joints, drive shaft, and differential or rear axle.

The clutch is a friction device that connects and disconnects a driving force from a driven member. It is designed to provide smooth and positive engagement and disengagement of the engine and manual transmissions. It is also needed because internal combustion engines develop less torque at low rpm's and must gain engine rpm's before the vehicle will move. A gradual application of load and some slowing of engine speed are needed to provide smooth starts without stalling the engine. In vehicles equipped with manual transmissions, the gradual load application is accomplished by means of a clutch. If equipped with an automatic transmission, a fluid type clutch or **torque convertor** is used.

All of our fire apparatus use an Allison automatic transmission, so this chapter will not go into detail on clutches and manual transmissions. To envision how a torque
convertor works, picture a pinwheel facing an electric fan. When the fan blows air on the pinwheel, the pinwheel turns. The torque convertor consists of three elements: pump, turbine, and stator. The pump is the input element and is driven directly by the engine. The turbine is the output element and is hydraulically driven by the pump. The stator is the reaction (torque multiplying) element. When the pump turns faster than the turbine, the torque convertor is multiplying torque. When the turbine approaches the speed of the pump, the stator starts to rotate with the pump and turbine. Torque multiplication stops and the torque convertor functions as a fluid coupling when the stator is rotating.

Converter Flow

Inside the torque convertor is a lockup clutch that consists of three elements: piston, clutch plate, and back plate. The piston and back plate are driven by the engine. The clutch plate, located between the piston and the back plate, is splined to the convertor turbine. The lockup clutch is engaged and released according to electronic signals sent from the ECU (Electronic Control Unit). The lockup clutch also engages when the apparatus reaches a predetermined speed. Engagement of the lockup clutch provides a direct drive from the engine to the transmission gearing. This eliminates convertor slippage to provide better fuel mileage. At lower speeds, the lockup clutch releases. When it releases, drive from the engine is transmitted hydraulically through the convertor to the transmission gearing. The lockup clutch also releases when the ECU detects certain undesirable conditions.

A series of planetary gears and shafts provide the gear ratios and direction of travel for the vehicle. A planetary gear set has three major elements:

— Sun gear
— Planet carrier, drum, and pinions
The name "planetary gears" is derived from the similarity of the gears to our solar system. Each pinion (planet gear) turns on its own axis while rotating around the sun gear. The pinion gears are surrounded by the ring gear. Power flow through the planetaries is controlled by clutch packs, which are applied and released hydraulically in response to electronic signals from the ECU. Through the control of the various planetaries, the clutch packs can function as driving elements or driven elements. The planetary gears for forward speeds are used in one form as a reduction gear (output of transmission slower than input) and in another as an overgear (output of transmission faster than input).

On the output side of some Allison automatic transmissions is a device known as an output retarder. It consists of a multiplate clutch pack and a vaned rotating element. When the retarder is applied, a control valve instantly releases oil to fill the retarder cavity and applies the retarder clutch. The clutch and rotating element act together to quickly slow the vehicle. It is effective over a wide range of speeds. Use the retarder any time you want to slow down. Observe the following cautions when using vehicles equipped with any type of input or output retarder (also known as Jake Brake, Maxi Brake, and Brakesaver):

— DO NOT USE THE RETARDER WHEN OPERATING WITH AN EMPTY TANK OR ON ROAD SURFACES THAT ARE SLIPPERY OR WET. DEENERGIZE THE SYSTEM AT THE MASTER CONTROL SWITCH.
— OBSERVE ENGINE AND TRANSMISSION TEMPERATURE LIMITS AT ALL TIMES.
— IF OVERHEATING OCCURS, REDUCE VEHICLE SPEED TO REDUCE RETARDATION POWER REQUIREMENTS.

Hopefully, by this point in the chapter, you understand how power is created in the engine and how it flows from the engine into and through the transmission. On structure fire apparatus, you next have the pump which routes the power according to design and the position of the controls in the cab and on the pump panel. Assuming the pump is not in gear and the vehicle is moving down the road, you next come to the driveline which has the job of connecting the transmission with the driving axles. The engine and transmission are securely mounted to the frame while driving wheels are free to move up and down in relation to the frame. This freedom of movement causes constant changes in the angularity of the driveline components which are: universal joints, drive shaft, and differential drive pinion. To accommodate these changes in angularity, flexibility is needed in the drive train, and it is provided by universal joints.

A universal joint (u-joint) is a mechanical device that can transmit torque and/or rotational motion from one shaft to another at fixed or varying angles. Most common is a u-joint at each end of the drive shaft. On longer applications, you can have multiple shafts with additional sets of u-joints for each shaft. The drive shaft usually is tubular steel with a yoke on each end that connects to the u-joints and each end of the driveline.

The rear axle assembly or differential is a gear system that transfers power at right angles from the drive shaft to the driving axles. Since the driving axles are splined to the differential side gears at right angles to the line of drive, the differential assembly uses a drive pinion gear and ring gear to redirect the transfer of power to the driving axles. This assembly also permits one driving wheel to turn faster than the other to prevent skidding or scuffing of tires while negotiating turns.