2.0 INTRODUCTION TO DIESEL ENGINES

This chapter presents the basic theory and principles of design which show how the chemical energy in fuel oil is converted into rotational shaft output horsepower by means of the diesel engine.

Learning Objectives

As a result of this lesson, you will be able to:

1. Explain the basic energy conversion process resulting from the operation of a diesel engine.

2. Differentiate between the operating principles of 4-stroke cycle and 2-stroke cycle diesel engines.

3. Identify selected basic terms applicable to the design and operation of a diesel engine.

4. Describe the basic heat/power balance which exists during the operation of a diesel engine.

2.1 Introduction to Emergency Diesel Generators

Electrical power is normally supplied to the nuclear utility by the power grid to which the plant is connected. Should this source of power become unavailable, known as a Loss Of Offsite Power (LOOP), some alternate power source must be available to power the essential electrical loads. This alternate power is provided by the plant Emergency Diesel Generators or EDGs

The EDGs are designed to start automatically in the event of a LOOP or other emergency signal. They may also be started manually when the plant operators determine a threatening or potentially hazardous condition exists. Once on line, these diesel generators must be able to supply the plant's dedicated electrical needs for as long as necessary to allow the plant operators to reach a safe shutdown condition and maintain that condition until the offsite electrical supply is re-established.

2.2 Energy Conversion

Diesel engines are, by nature, energy conversion devices. In a nuclear application, the energy contained in the fuel supplied to the engine is converted into the electrical energy needed to ensure the safe shutdown of the plant. This process requires three steps:

First, the chemical energy contained in the fuel oil is converted into thermal energy by the process of combustion.

Second, this thermal energy, in the form of heated gases, is converted into mechanical energy by expansion cooling of the gases. This creates the forces on the pistons, connecting rods and crankshaft. These components convert the linear motion of the piston into rotational output shaft horsepower.

Third, the generator, through electro-magnetic induction, converts the mechanical energy supplied by the engine into the required electrical energy. This process will be discussed in more detail in Chapter 9.

2.2.1 Combustion

Combustion is defined as: *The chemical reaction between the elements of hydrogen and carbon (supplied by the fuel) and oxygen (sup- plied by free air) resulting in the release of energy in the form of heat and light.*

For combustion to occur, three (3) key elements must be present. Elimination of any one of the three will prevent combustion from occurring.

Fuel, which is comprised primarily of carbon and hydrogen, supplies the energy to be converted. Within the engine cylinders, the chemical energy of the fuel is converted into thermal energy. On an average, diesel fuel oil contains energy of approximately 140,000 Btu's per gallon.

Oxygen is the second key element of the combustion process. It combines with the carbon and hydrogen of the fuel to produce the products of light and heat. In a diesel engine, the oxygen is supplied by the intake of atmospheric air.

Heat of sufficient value is required to cause ignition of the fuel and air mixture. This heat comes from the rapid compression of the atmospheric air charge confined within the cylinder.

The combustion process will be discussed in more detail in Chapter 4, "Fuel, Air, and Engine Governing."

2.2.2 Cylinder Activity

In order to fully comprehend the operation of a diesel engine and how each of the components is necessary to support that operation, we must have a solid understanding of the combustion process as it occurs within the diesel engine.

2.2.2.1 Closed Container (Figures 2-1, 2-2)

We will begin with the closed container shown in Figure 2-1. It has been charged with a mixture of fuel and air in the proper proportions for combustion to take place. The pressure and temperature of the contents of the container are at equilibrium with its surroundings.

With the addition of heat, ignition of the fuel and air occurs as shown in Figure 2-2. The combustion causes a sharp rise in both temperature and pressure within the container. Since the volume of the container is fixed, no movement can occur and therefore no work is accomplished.

2.2.2.2 Addition of Piston (Figures 2-3, 2-4)

By adding a movable piston to the bottom of the container, we still have a confined space, but the volume is now variable. A charge of fuel and air is placed above the piston as before. With the addition of heat to ignite the air fuel mixture, combustion occurs causing the temperature and pressure to rise sharply. This rise in pressure causes the piston to move downward rapidly, forcing it out of the bottom of the container. No useful work is provided, but there is movement.

2.2.2.3 Connecting Rod and Crankshaft (Figures 2-5, 2-6)

The problem we face is how to convert the thermal energy of combustion into the mechanical energy required to operate the generator. We know from the fundamentals of mechanical design that by adding a crankshaft and connecting rod to the piston and cylinder, we can convert the linear motion of the piston into rotary motion of the crankshaft.

We now have a configuration as shown in Figure 2-5. The connecting rod makes the physical connection between the piston and the crankshaft. The area above the piston, the combustion chamber, is charged with an air fuel mixture.

By adding the heat needed to ignite the air fuel mixture, combustion will occur causing a rapid increase in temperature and pressure above the piston. This pressure then forces the piston downward. The connecting rod transmits the force of the piston to the crankshaft causing it to rotate 180 degrees as shown in Figure 2-6.

2.2.3 Four-stroke Cycle Operation

The activity up to this point is limited to only 180^{o} of crankshaft rotation. The useful work output of the engine, therefore, is also limited. The problem now is to find a way to make this process repeatable for each cylinder.

2.2.3.1 Operational Requirements

To make this process repeat, creating a continuous rotation of the crankshaft the following series of events must take place.

- A fresh charge of air must be supplied to each cylinder in preparation for the next combustion cycle.
- This fresh air charge must be heated above the ignition temperature for the fuel oil supplied.
- Once heated above the ignition temperature, a specific quantity of fuel must enter the combustion chamber and mix with the air charge in such a manner that combustion will occur.
- The mechanical components of the engine will then convert thermal energy into the required mechanical energy.
- The spent gases must be removed to allow for a fresh air charge to enter the cylinder.

2.2.3.2 Cylinder Configuration (Figure 2-7)

To fulfill these requirements, a cylinder arrangement as shown in Figure 2-7 is constructed. This configuration is typical of 4-stroke cycle diesel engine;. 2-stroke cycle diesel engines are discussed later in this chapter.

- A **cylinder,** or cylindrical volume is created with a fixed upper closure (cylinder head).
- A **piston** forms the closure at the lower end of the cylinder and transmits the forces of combustion through the **connecting rod** to the crankshaft.
- A **crankshaft** works in conjunction with the connecting rod and piston to convert the linear motion of the piston to the required rotary motion.
- An **exhaust valve** is placed in the upper closure of the cylinder to provide a path for removal of spent gases from the combustion space.

- An **intake valve** is also added to the upper closure. It provides a means for directing a fresh air charge into the cylinder.

- A **fuel injector** is added to provide a method for delivering fuel to the air charge once the air charge has been sufficiently heated.

- The **heat** required to ignite the fuel is obtained by rapidly compressing the air charge. This will be detailed in the following paragraphs.

Diesel engine operation is based on the air standard Diesel cycle shown in Figure 2-12. The graph plots the pressure in the cylinder against the volume of the cylinder as the piston moves through its cycle. Beginning at point 1, the piston is at the bottom of its stroke with the cylinder volume the greatest.

As the air charge is compressed, the pressure increases as the volume decreases from point 1 to point 2. Point 2 represents the highest pressure at which time fuel is injected into the cylinder. With this ideal cycle, combustion occurs at a constant pressure while the cylinder volume increases from point 2 to point 3. Combustion is complete at point 3 where the gas pressure decreases as the volume increases from point 3 to point 4.

At point 4, the volume is at its maximum, exhausting the spent gases and refilling the cylinder with a fresh air charge.

Figure 2-14 represents the actual pressure versus stroke activity in the cylinder of a 4-stroke cycle diesel engine. This graph will be referenced in sections 2.2.3.3 thru 2.2.3.7.

2.2.3.3 Intake of Air Charge (Figure 2-8)

We begin the 4-stroke cycle process with the cylinder in the configuration as shown in Figure 2-8. The piston is at the top of its stroke and the intake valve is open. Rotation of the crankshaft causes the piston to move downward. This downward movement of the piston causes a negative pressure to develop within the cylinder. This is shown between points A and B on the graph provided in Figure 2-14. Atmospheric pressure, being higher than that in the cylinder, pushes a charge of air into the cylinder. Once the piston has reached the bottom of its stroke, the cylinder should be fully charged with fresh air.

2.2.3.4 Compression of the Air Charge (Figure 2-9)

Once the piston has reached the bottom of its stroke (point B), the intake valve closes. This traps the air charge in the cylinder. Further rotation of the crankshaft moves the piston upward. This movement of the piston compresses the air charge, sharply increasing its pressure and temperature. As the piston approaches the top of its stroke, the air charge has been heated above the temperature required to ignite the fuel oil.

2.2.3.5 Injection of Fuel (Figure 2-10)

A short distance before the piston reaches the top of its stroke, a specific quantity of fuel is injected into the heated air charge. The fuel mixes with the heated air in the cylinder and ignition occurs. This is represented by point C on the graph of Figure 2-14. As a result of this combustion, the pressure in the cylinder increases sharply as the piston moves past its uppermost point of travel (point D).

2.2.3.6 Development of Power (Figure 2-11)

The injection of fuel continues past the uppermost point of piston travel causing the combustion process to continue. The pressure in the cylinder continues to increase, reaching its peak (point E of Figure 2-14) shortly after the piston has passed its uppermost point of travel. The piston is now being forced downward by the expanding gases, delivering power to the crankshaft. The power being delivered to the crankshaft is indicated by the line D-E-F on the graph of Figure 2-14.

2.2.3.7 Exhaust of Spent Gases (Fig. 2-12)

Several degrees before the piston reaches the bottom of its stroke, the exhaust valve opens (point F of Figure 2-14). With the pressure in the cylinder still above atmospheric, the spent or burned gases begin to exhaust to the atmosphere. After reaching the bottom of its stroke, the piston again moves upward. This upward motion of the piston forces most of the remaining gases from the cylinder.

As the piston reaches the top of its stroke, represented by point A of Figure 2-14, the exhaust valve closes and the intake valve opens. This returns the cycle to its starting point and the engine is again ready to take in a fresh charge of air so that its operation may continue.

2.2.3.8 Four-stroke Cycle Operation

The process just described required four strokes of the piston or two revolutions of the crankshaft (720 degrees) to complete one power event. This process is therefore referred to as the 4-stroke cycle of operation or more commonly, a 4-stroke cycle diesel engine.

2.2.4 Two-stroke Cycle Operation - Conventional

During the development of the diesel engine, a means was discovered that allowed an engine to provide one power event for each revolution (360 degrees) of the crankshaft, or two strokes of the piston. As would be expected, this process became known as the 2-stroke cycle of operation.

The following information is representative of the General Motors, Electro-Motive Division (EMD), Series 567, 645 and/or 710 diesel engines, frequently used for Emergency Diesel Generators at commercial nuclear facilities.

2.2.4.1 Cylinder Configuration (Figure 2-15)

The 2-stroke cycle cylinder configuration shown in Figure 2-15 varies somewhat from that of the 4-stroke cycle configuration discussed previously. It retains the exhaust valves and fuel injector mounted in the cylinder head as found in the 4-stroke cycle engines. However, the intake valves have been replaced by ports cut through the wall of the cylinder as shown. Intake of the air charge will only occur when the top of the piston is below the intake ports in the cylinder wall.

One problem associated with the 2-stroke cycle of operation is that during the intake and exhaust events, the air must be pumped into the cylinder. Generally, these engines use a mechanically driven blower and/or exhaust driven turbocharger to force the air into the cylinder for combustion and removal of the spent gases. Blowers and turbochargers will be covered in detail in Chapter 4, "Fuel, Air and Engine Governing."

2.2.4.2 Intake Event (Figure 2-16)

The 2-stroke cycle begins with the piston at the bottom of its stroke with the intake ports uncovered and the exhaust valves open. Air, supplied by the blower, is forced through the intake ports into the cylinder. Some of this air is used to push the remaining spent gases out of the cylinder past the exhaust valves.

As the piston begins to move upward, the exhaust valve closes. The blower continues to provide pressurized air to the cylinder until the piston has moved up sufficiently to close off the intake ports. This completes the intake event.

2.2.4.3 Compression (Figure 2-17)

Once the piston has closed off the intake ports, the upward movement of the piston compresses the air charge, raising its temperature above that needed to cause ignition of the fuel. As with the 4-stroke cycle engines, as the piston approaches the top of its stroke, fuel is injected into the heated air charge. The resulting ignition of the fuel begins the combustion process.

2.2.4.4 Combustion and Power (Figure 2-18)

As the piston passes its uppermost point of travel, the expanding gases of combustion force it downward delivering power to the crankshaft. Power continues to be delivered to the crankshaft until shortly before the piston reaches the intake air ports. At this point the exhaust valves open ending the power event.

2.2.4.5 Exhaust Event

Once the exhaust valves have opened, the spent gases, having a pressure greater than atmospheric pressure, begin to exhaust from the cylinder. Continued downward movement of the piston opens the intake ports allowing the intake air, under pressure from the blower, to enter the cylinder, scavenging (removing) the remaining spent or burned gases.

The piston has now reached the bottom of its stroke, and with both the exhaust valves open and the intake ports uncovered, the cycle is ready to repeat as the piston moves upward. This cycle of events has occurred in only two strokes of the piston or 360 degrees of crankshaft rotation.

2.2.5 Two-stroke Cycle Operation -- Opposed Piston

A variation of the 2-stroke cycle of operation, which has been in commercial use since before World War II, is the opposed piston engine. This unique design shown in Figure 2-19 uses two pistons (upper and lower) per cylinder. There are also two connecting rods and two crankshafts. The engine uses no valves. Both the intake air and exhaust gases flow through ports in the cylinder wall. The fuel injection nozzles are placed through the cylinder wall near the center.

2.2.5.1 Intake Event (Figure 2-20)

The process begins with both pistons near their outermost points of travel. Both the intake and exhaust ports are uncovered. The incoming air charge, being forced in by a blower and/or turbocharger, fills the combustion space while pushing the remaining spent gases from the cylinder through the exhaust ports.

It should be noted that the lower piston/crankshaft leads the upper by approximately 15^o of crankshaft rotation. This is done to ensure that the exhaust ports are closed before the intake ports during inward movement of the piston. With the exhaust ports closed and the intake ports still open, the incoming air slightly pressurizes the cylinder. As the upper piston closes the intake ports, the intake event is completed.

2.2.5.2 Compression (Figure 2-21)

With both ports closed, the air charge is captured and compression of the air charge begins. Compression continues until both pistons are near their innermost points of travel. With the 12 to 15□ lead between the lower and upper crankshafts, both pistons will not reach their innermost points of travel at the same time.

2.2.5.3 Combustion and Power (Figure 2-22)

As the pistons approach their innermost points of their travel, the air charge is fully compressed and its temperature has reached the ignition point for the fuel. A metered quantity of fuel is then precisely injected into the heated air mass and combustion occurs. As the combustion gases expand, they force the pistons away from each other transmitting power to both crankshafts.

2.2.5.4 Exhaust Event (Figure 2-20)

Downward motion of the lower piston, with its lead, uncovers the exhaust ports allowing the exhaust gases to begin to escape. The upper piston then uncovers the intake ports allowing the incoming air charge to help push the spent gases from the cylinder.

With both pistons near the outermost points of their travel, the cycle is ready to be repeated for continuous operation of the engine. As with the 2-stroke conventional engine, the opposed piston engine also delivers one power event for every two strokes of the piston, or 360 degrees of crankshaft rotation.

2.2.6 Two-stroke vs Four-stroke Cycles

Theoretically, for two engines of similar configuration and size, one being a 4-stroke cycle and the other a 2-stroke, the 2-stroke engine should be able to develop twice the power of the 4-stroke. However, the 2-stroke engine requires horsepower to drive the blower which reduces the actual horsepower available for work. Further, incomplete scavenging and a reduced effective stroke length as the piston passes the intake ports of a 2-stroke cycle engine limits the power output of the engine.

If one looks at Figure 2-14 again and applies it to the 2-stroke cycle engines, it is basically the same from point B (at the point the Intake Valve/port closes) to point F (the point that the exhaust valve/port) opens, and substitutes another means of charging the cylinder with air between those two points (B-valve closed to F), then the diagram applies to the 2-stroke cycle engine just as well.

Selection of an engine type, 2-stroke or 4-stroke, for a particular application becomes a decision based on engineering data, economics, and personal preference. Both types of engine perform satisfactorily and reliably when proper maintenance and operating procedures are followed.

2.2.7 Typical Times for All Events
(Figures 2-26 and 2-27)

Each event must occur smoothly, within a few milliseconds, and at precisely the right time for satisfactory engine operation.

2.3 Diesel Engine Terminology

2.3.1 Dimensional Specifications
(Figure 2-23)

2.3.1.1 Cylinder Bore

This is the specified inside diameter of the engine cylinder. Its nominal size is given in inches and fractions. For example, the nominal bore of a Fairbanks Morse, Model 38TD8-1/8 opposed piston engine is 8 and 1/8 inches. Actual bore, for manufacturing and maintenance purposes, will be specified in inches and decimals. For the same engine, the bore indicated in the maintenance manual is 8.125 to 8.129 inches.

2.3.1.2 Stroke

This dimension represents the total distance traversed by the piston as it moves from the top of its stroke to the bottom and vice versa. Specified in inches and fractions, it is equal to twice the length of the crankshaft throw. Combining the bore and the stroke gives the cylinder displacement as described in section 2.3.1.7.

2.3.1.3 Top Dead Center (TDC)

This term is applicable to 4-stroke cycle and 2-stroke cycle conventional engines. Rather than a dimension, it represents the position of the piston when it is at the top or uppermost point of its stroke. References to injection timing or crankshaft position are termed as degrees before or after TDC. For example, injector timing may be set to 23^{o} before TDC while exhaust valve closure may be 15^{o} after TDC.

2.3.1.4 Bottom Dead Center (BDC)

As would be expected, this term is the opposite of Top Dead Center, the lowermost point of piston travel. Some specifications are given relative to BDC. For example, inlet valve closure would normally be given as 7^{o} after BDC.

2.3.1.5 Inner Dead Center (IDC)

This term, similar to TDC for 4-stroke and 2-stroke conventional engines, is uniquely applicable to 2-stroke cycle opposed piston (OP) engines. It represents the piston position at its innermost point of travel. Keep in mind, however, that both pistons do not reach IDC at the same time due to the lead of the lower crankshaft.

2.3.1.6 Outer Dead Center (ODC)

This term references the piston position at the outermost point of its stroke. It is here that intake ports and the exhaust ports are fully open (uncovered). Due to crankshaft lead, the pistons do not reach ODC at the same time.

2.3.1.7 Cylinder Displacement

The power an engine is capable of developing is relative to the amount of fuel the engine can burn efficiently. In turn, the amount of fuel which can be burned depends on the volume of air or displacement of the cylinder.

Cylinder displacement (D) is the volume displaced by the piston as it moves from TDC to BDC or BDC to TDC.

Numerically, this is calculated by multiplying the cross-sectional area of the cylinder by the length of the stroke (L). The following formula will determine the displacement of a single cylinder.

$$D = \frac{\pi d^2}{4} * L$$

(All in inches or same dimensional units)

To determine the total displacement (TD) of an engine, simply multiply the displacement of 1 cylinder by the number of cylinders (N).

$$D = \frac{\pi d^2}{4} * L * N$$

Hereafter, the total engine displacement will be referred to as DISP.

2.3.1.8 Clearance Volume (Figure 2-24)

Clearance Volume (CV) represents the total volume of the cylinder when the piston is at Top Dead Center. This volume includes the cylindrical volume between the piston and the cylinder head including any volume created by the shape of the top of the piston and/or cylinder head combustion space.

2.3.1.9 Compression Ratio (Figure 2-24)

The compression ratio (CR) of an engine is the ratio of the <u>volume</u> of the cylinder with the piston at BDC (D+CV) to the <u>volume</u> of the cylinder with the piston at TDC (CV). It can be represented numerically as follows.

$$CR = \frac{D + CV}{CV} = \frac{D}{CV} + 1$$

This can be simplified as follows.

$$\frac{StrokeLength(L) + C}{C}$$

Where 'C' represents the clearance distance between the piston and cylinder head. This method gives only an approximation when the actual clearance volume is not known.

Compression ratios for diesel engines can run from as low as 8:1 for large, low speed units to 21:1 for smaller, high speed automotive types. It should be recognized that on a turbocharged engine the actual compression ratio in the cylinder is the product of the swept volume compression ratio (from the piston motion) and the pressure ratio of the turbocharger compressor and may approach 20-30 to 1.

2.3.2 Engine Performance

2.3.2.1 Horsepower

The term Horsepower used alone usually represents the power output of the unit. However, there are different types of horsepower which must be considered when discussing diesel engines

Brake Horsepower (BHP) - represents the net power output of the engine at the crankshaft. The term "brake" indicates that the power was measured by applying a braking device, sometimes called a "prony" brake, to the unit to measure its output in terms of torque per unit of time. With the diesel engine operating at a specific speed (RPM), the brake is applied until the engine can no longer maintain its set RPM. At this point, the torque is measured and converted into horsepower using the following equation.

$$BHP = \frac{TN}{5252}$$

T = torque in foot-pound
N = engine speed in RPM.

Indicated Horsepower (IHP) - is the total power developed by the engine. It is a function of the mean indicated pressure applied to the top of the piston.

$$IHP = \frac{P_i LAn}{33{,}000}$$

P_i = indicated mean effective pressure (psi)
L = length of stroke (ft.)
A = area of piston (in^2)
n = number of power strokes per minute

If the stroke (L) is given in inches, then the constant becomes 396,000

If LA is for a cylinder, then the IHP is that of a single cylinder. If DISP is substituted for LA, then the IHP is that for the whole engine.

Frictional Horsepower (FHP) - represents the power required to operate the engine. It is used to overcome friction, operate engine components and move air into and gases out of the engine.

The relationship between these three horsepowers is as follows:

$$BHP = IHP - FHP$$

2.3.2.2 Torque (T)

Torque represents a twisting or turning effort. Torque may involve rotary motion or no motion at all. For diesel engines, torque is the turning effort exhibited by the crankshaft. Since there is rotary motion of the crankshaft, there is a definite relationship between this torque and the brake horsepower produced by the engine.

$$T = \frac{5252 * BHP}{N}$$

The Brake Torque can also be determined by the following formula:

$$T = BMEP \cdot DISP / 75.4$$

2.3.2.3 Brake Mean Effective Pressure (BMEP)

This is a theoretical term, shown in the equation below as P_b, representing the mean effective pressure for each power stroke which produces the rated brake horsepower of the engine.

Numerically for 4-stroke cycle engines;

$$P_b = \frac{792{,}000 * BHP}{D * N}$$

Numerically for 2-stroke cycle engines;

$$P_b = \frac{396{,}000 * BHP}{D * N}$$

D = DISP - displacement of the engine
N = number of revolutions per minute
P_b = brake mean effective pressure in psi and is often represented by the symbol 'BMEP'.

2.3.3 Engine Efficiency

2.3.3.1 Mechanical Efficiency (e_m)

Mechanical efficiency is the ratio of the power output of the engine (BHP) to the indicated power input (IHP). Numerically;

$$e_m = \frac{BHP}{IHP}$$

2.3.3.2 Thermal Efficiency (e_t)

This represents the energy output of the engine to the heat input of the fuel over a period of time. One horsepower is equal to 2545 BTUs per hour.
For example: What is the thermal efficiency of an engine which produces 1000 BHP while consuming 50 gallons of fuel per hour? Assume fuel with a heat value of 140,000 Btu's per gallon.

Heat input of fuel;

50 gal/hr x 140,000 BTUs/gal =
7,000,000 BTUs/hr

Engine power output;

1000 hp x 2545 BTU/hr. hp. =
2,545,000 Btu's/hour

Thermal efficiency becomes;

$$\frac{2{,}545{,}000}{7{,}000{,}000} = 0.364 = 36.4\%$$

Since only about one-third of the energy input of the engine is converted into usable power, the remaining two-thirds is rejected to the environment as follows:

2.3.3.3 Heat Balance

This represents the balance of the engine heat input (100%) to the heat energy lost to the environment during the operation of the engine:

- Power output (BHP) = 33 - 40%
- Exhaust and radiation = 30- 33%
- Jacket water cooling = 10 - 15%
- Lube oil cooler = 4 - 8 %
- Turbocharger aftercooler = 5 - 10 %
- Generator Inefficiency = 3 to 5%
- Radiation (engine to room) = 2%

Heat balances are performed by measuring the temperatures of the fluids entering and leaving the engine and knowing the fluid flows. This allows computation of the heat being rejected to a system such as the lube oil, the jacket water, or the air system. The exhaust system figure is generally found by subtracting all of the other known systems from the total heat computed from the heat input of the fuel. See BSFC below.

2.3.3.4 Volumetric Efficiency

This term is normally applied to non-turbocharged 4-stroke cycle engines. It is an indication of the engines ability to breathe. Numerically, it is the ratio of the volume of fresh air taken into the cylinder to a volume of air equal to the displacement of the cylinder. A volumetric efficiency of 1 indicates the cylinder has taken in a full charge of fresh air.

2.3.3.5 Scavenging Efficiency

This term, applicable to 2-stroke cycle engines, is the ratio of the new air charge trapped in the cylinder compared to the total volume of air and exhaust gases in the cylinder at the time of port closing.

2.3.3.6 Brake Specific Fuel Consumption (bsfc)

BSFC is an indication of the engines fuel efficiency. It is based on the rate of fuel consumption per hour per horsepower output of the engine.

$$bsfc = \frac{FuelBurned(lbm)/hr}{BHP}$$

The results are normally given on the basis of pounds of fuel per horsepower hour, but may also be on the basis of gallons per horsepower hour. For electric generation, it may be given as pounds or gallons of fuel per kilowatt hour.

2.3.4 Additional Terminology

2.3.4.1 Supercharging

During operation of a diesel engine, atmospheric pressure provides the force needed to cause the intake air charge to enter the engine cylinder. Engines which rely on atmospheric pressure for their intake air charge are referred to as "naturally aspirated.” By providing an air pumping device to the engines intake air system, it is possible to increase the pressure and subsequently the mass flow of air entering the cylinder. Whenever the mass of air entering the cylinder is greater than that which would be attained by atmospheric conditions, the engine is said to be supercharged.

When an engine is supercharged, a greater mass of the air enters the cylinder, providing an increased quantity of oxygen available to support combustion. With this increase in available oxygen, the engine can burn more fuel and therefore develop more horsepower (BHP).

2.3.4.2 Blower or Supercharger

These terms, often used interchangeably, apply to the mechanical devices which are used to increase the mass of air entering the engine cylinder. Such devices are usually mechanically driven by the engine and therefore require horsepower from the engine for their operation. Their output, mass of air, is a function of the rpm of the engine.

2.3.4.3 Turbocharger

This is another device used to increase the intake air mass for a diesel engine and therefore increase its power output. The key difference between a Turbocharger and a Blower or Supercharger is that the turbocharger is powered by the energy of the heated exhaust gases leaving the engine. It therefore does not require horsepower directly from the engine, making the overall process more efficient. It does, however, represent a restriction to the flow of exhaust gas producing an increased back-pressure in the exhaust system. The power increase resulting from the addition of the turbocharger more than offsets the slight power lost due to the increased back pressure.

Additionally, since the volume of air discharged by the turbocharger is a function of the heat energy of the exhaust gases, the turbocharger tends to respond to the load imposed on the engine. The greater the engine load, the greater the heat energy in the exhaust. With the increased heat energy, the turbocharger produces an increased boost to the intake air charge. Initially, the process was described as being Turbo-supercharged. But over time, it has been simplified to Turbocharged.

Blowers and turbochargers will be discussed in greater detail in Chapter 4, "Fuel, Air and Engine Governing."

Another look at Figure 2-14 is warranted. The effect of turbocharging on this diagram is to raise the line at 14.7 (standard atmospheric pressure) to a higher line, say to 28 psia. This also raises the peak firing pressure point at E. To compensate for this (as this point may be limited by the strength of the parts of the engine), it is usually necessary to either reduce the compression ratio of the engine and/or retard the timing so that the pressure at point E is limited.

2.4 Typical Engine Design Criteria

There are some limits imposed by physical forces that limit the power output of an engine to ensure reliability and longevity. They are as follows:

BMEP - typical BMEP for 2-stroke cycle engines run from 150 to 160 BMEP.
For 4-stroke cycle engines, run from 300 to 320 psi BMEP.

Peak Firing Pressure - typically limited to 1200 to 1500 psi.

Piston Speed - 1500 to 2000 fpm (feet per minute). Piston speed = piston stroke (inches) $*2 *$ rpm **/** 12. An OP engine with 10-inch stroke at 900 rpm has a piston speed of 1500 fpm.

These limits advance slowly as engine technological and metallurgical improvements are made over time.

2.5 Chapter Summary

To summarize what we have learned in this lesson, let us look at Figure 2-27. This figure shows the timing diagrams for the typical 2- and 4-stroke engine cycles. The upper diagram shows the timing of the events in the 4- stroke cycle engine in a circular diagram. Remember that this engine requires two complete rotations in order to complete the events of the cycle.

There is a bar diagram in the center of this figure that shows the timing events along a line extending from 0 degrees to 720 degrees - two revolutions. The valve timing for the intake valves usually starts before the top of piston motion and overlaps the exhaust valve opening. Part of this is to better scavenge the cylinder. The other part is that it takes time, from the beginning of valve opening to get the valve fully open and to get full air flow into the cylinder.

Once the intake valve closes, shortly after the piston is past Bottom Dead Center, the trapped air is compressed. Near top dead center, the fuel is injected and shortly begins to burn, creating pressure in the cylinder. Note that while the injection is shown as a fixed length, in reality it varies in length proportional to the load requirement. On stationary engines, the start of injection is normally constant, always starting at the same crankshaft position. After injection, the piston moves down in the cylinder on the power stroke.

Near the end of the power stroke, the exhaust valve is opened, allowing the exhaust of the expended gases. The exhaust valve then stays open until slightly after the piston gets back to top dead center, allowing some overlap with the air valve for scavenging the cylinder. From this point, the cycle begins again.

The lower circle diagram shows the 2-stroke cycle opposed piston timing cycle. All events occur within one revolution. The cycle starts with the piston at outer dead center with the blower or turbocharger putting air into the cylinder. This not only fills the cylinder with air, but due to the overlap between the exhaust ports and air ports, allows the cylinder to be scavenged of exhaust from the last cycle. The exhaust ports are covered first as the lower piston moves up the cylinder. Shortly thereafter, the upper piston covers the air ports and compression begins.

As the pistons approach inner dead center, the exhaust piston arriving there first, the fuel is injected. As the fuel burns, pressure is created in the cylinder and the pistons are now moving apart. This is the power stroke. When the exhaust piston approaches outer dead center, it uncovers the exhaust ports and the expended gases are allowed to leave the cylinder. A few degrees later, the air ports also open and the fresh air charge enters the cylinder and purges the exhaust gases. The cycle then begins again.

Only one revolution was required. Note that the exhaust ports are centered on the outer dead center of the lower piston stroke while the air ports are centered above the upper piston outer dead center. If there were no crank-lead, then the exhaust ports would always be open when the air ports were also open, and there would be no opportunity to pack air into the cylinder before compression started.

The EMD 2-cycle engine would be similar to the OP engine diagram except that there would be no upper piston with its offset lead. The air ports would be opened by the motion of the piston, similar to the exhaust ports on the OP engine. The exhaust valves would be operated at the correct point in the cycle, such that they would open before the air ports opened to allow the cylinder to blow down, and they would close just after bottom dead center in order to trap air in the cylinder before compression starts when the air ports close.

These relationships will be covered again as the injection process is explained in Chapter 4

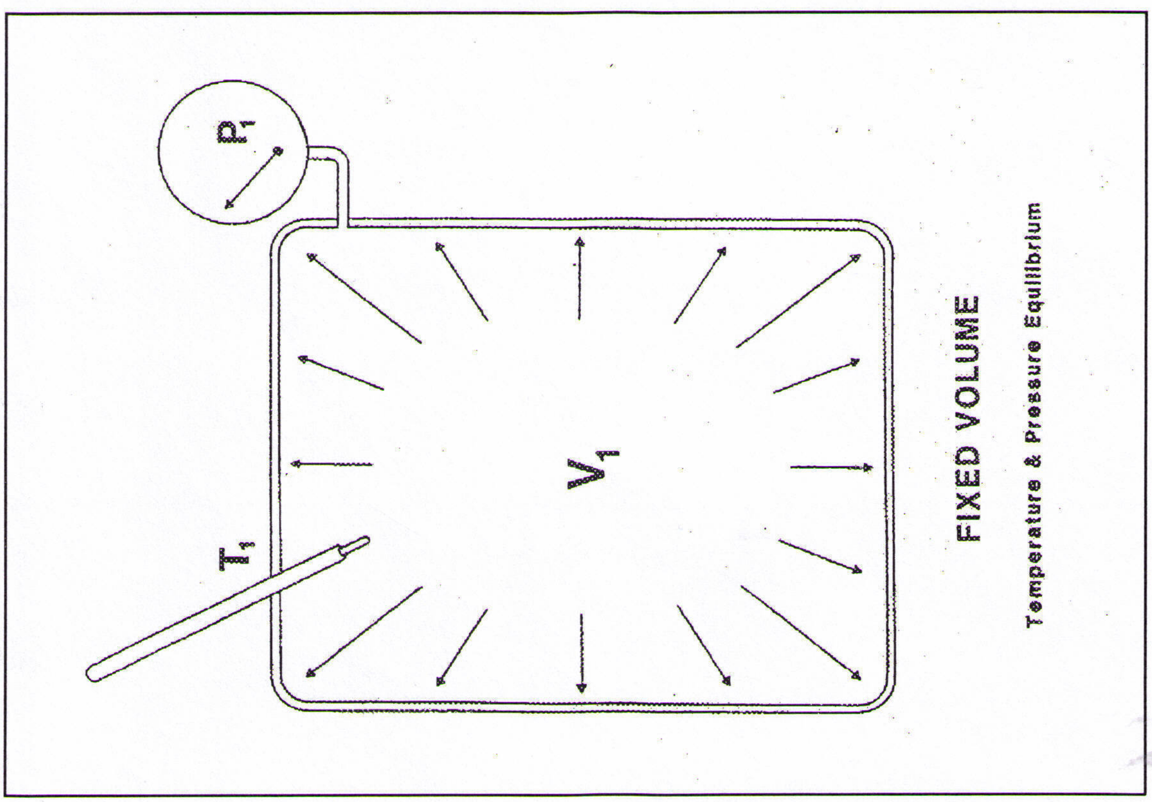

Figure 2-1 Fixed Volume

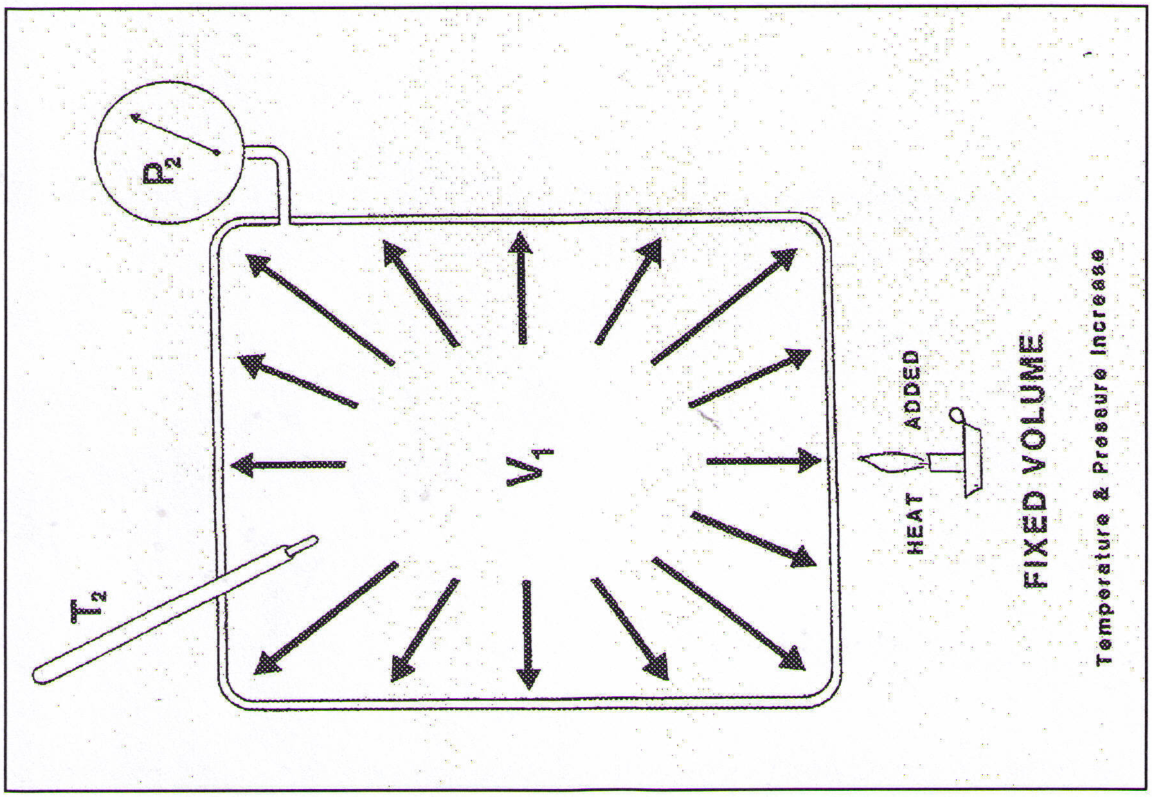

Figure 2-2 Fixed Volume Plus Heat

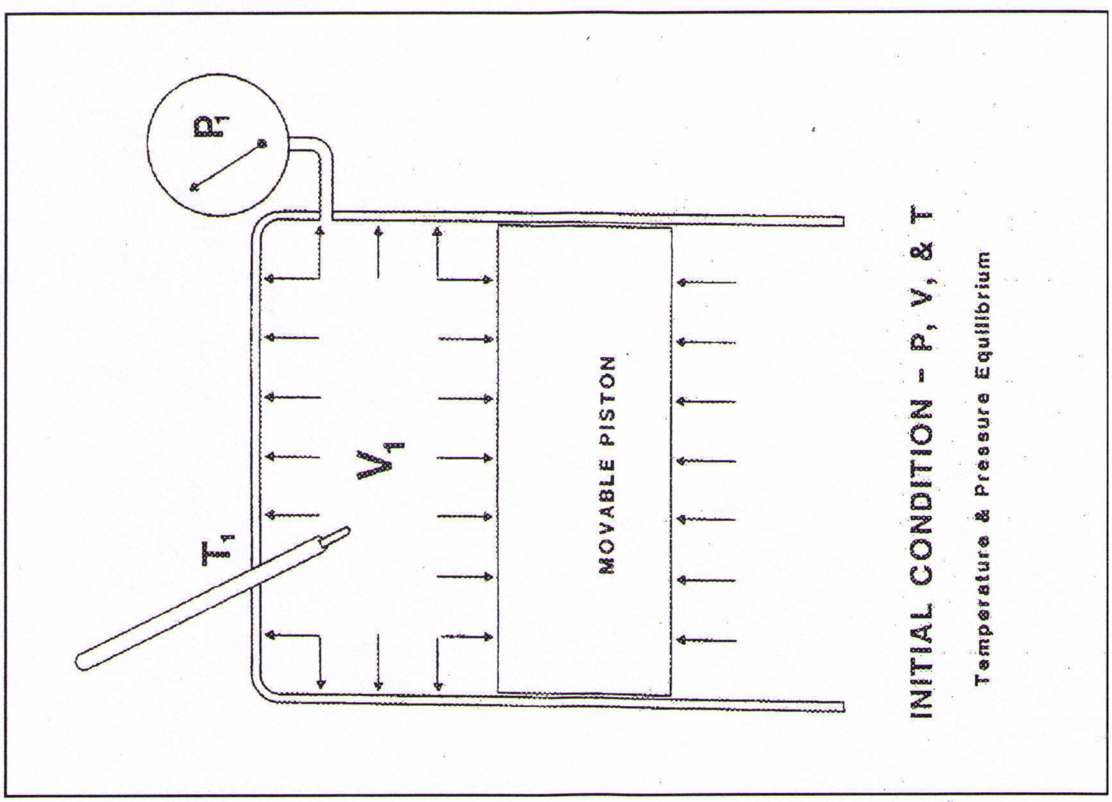

Figure 2-3 Addition of Piston

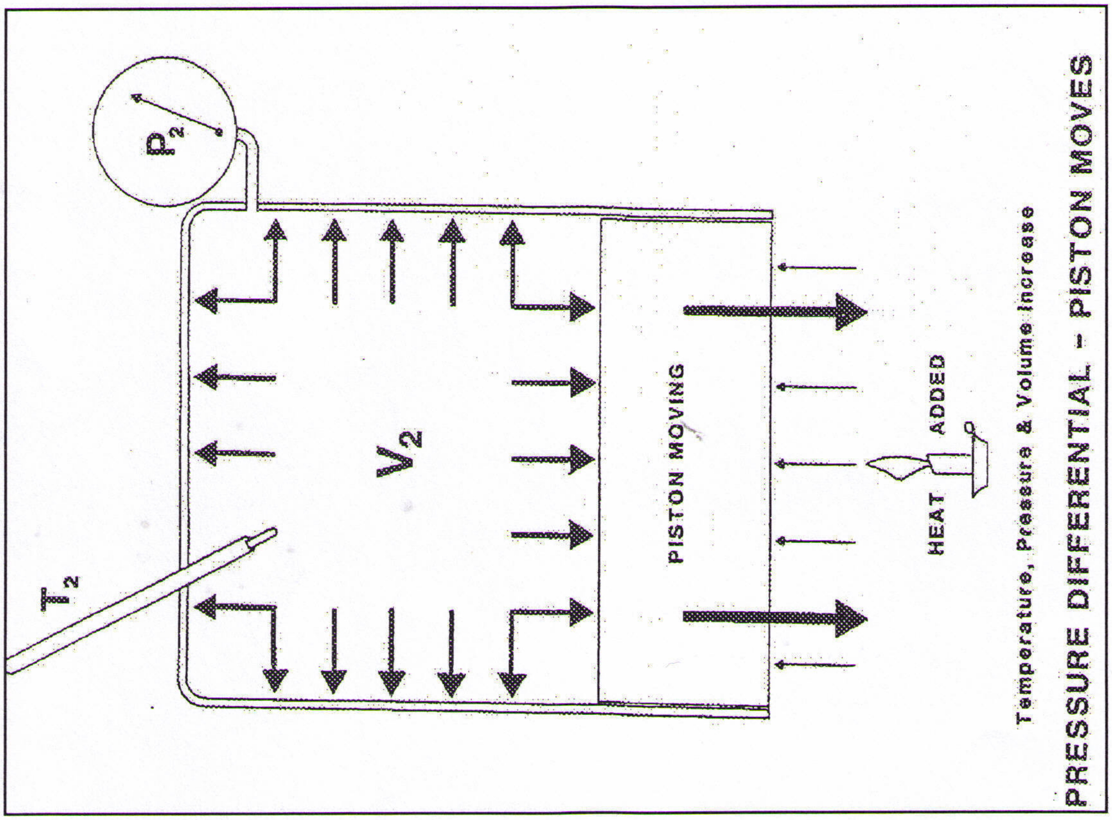

Figure 2-4 Addition of Piston Plus Heat

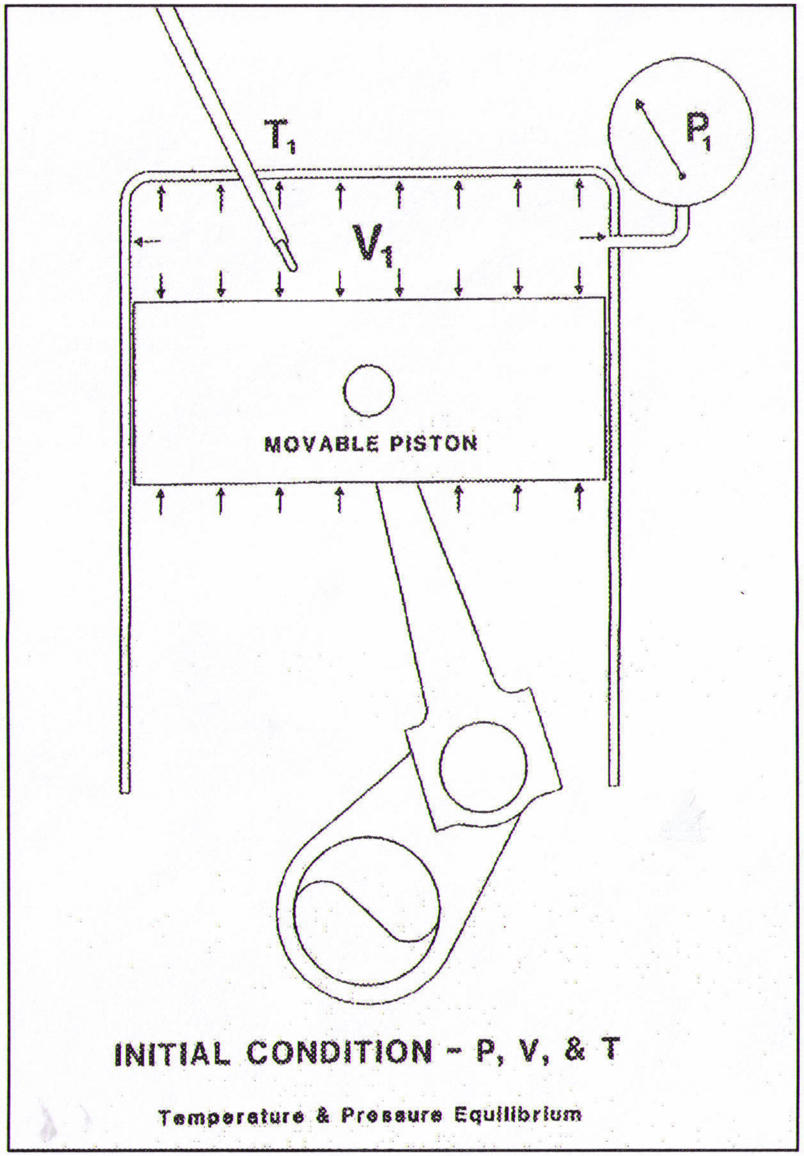

Figure 2-5 Addition of Crankshaft

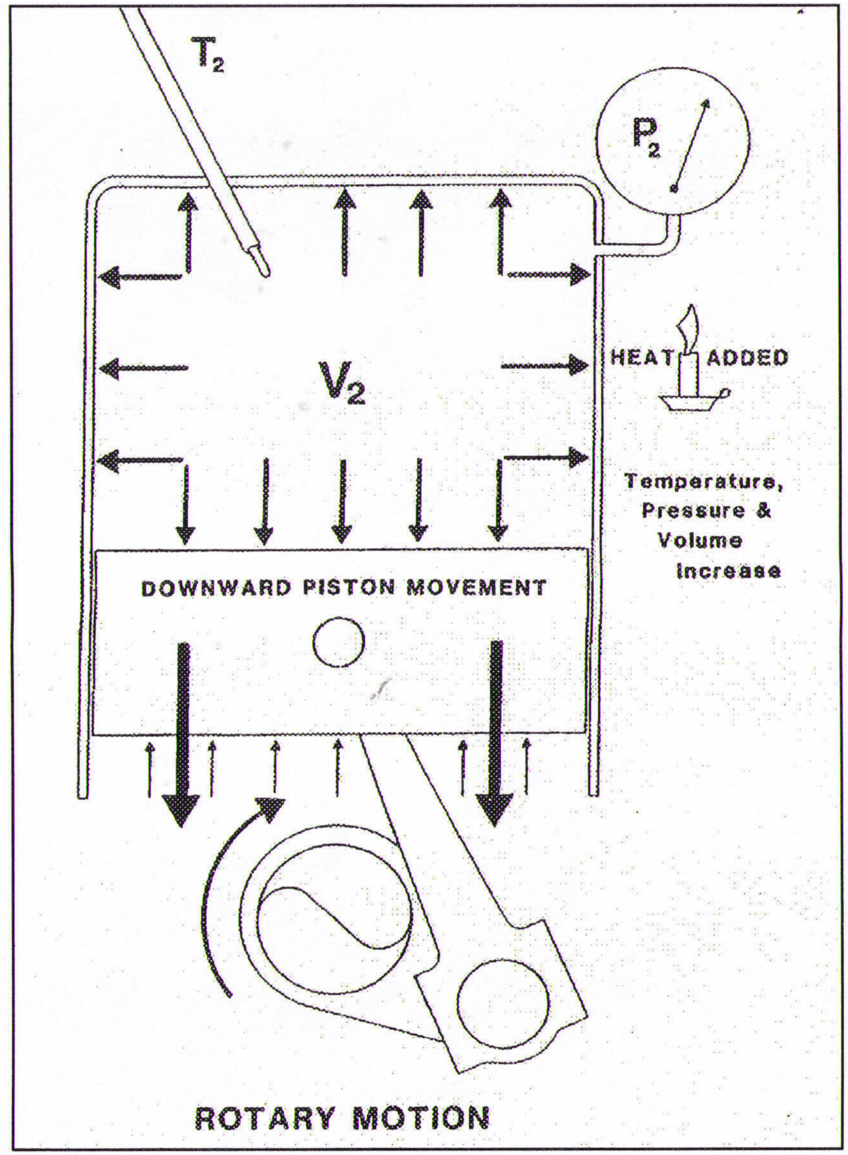

Figure 2-6 Addition of Crankshaft Plus Heat

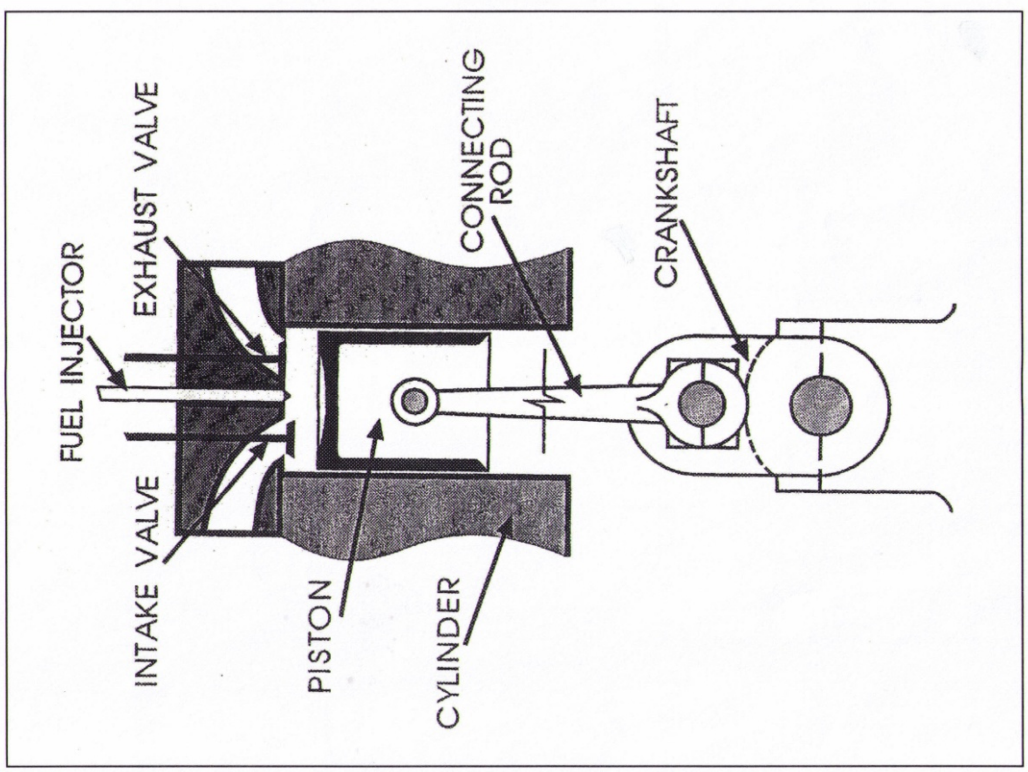

Figure 2-7 Cycle Configuration

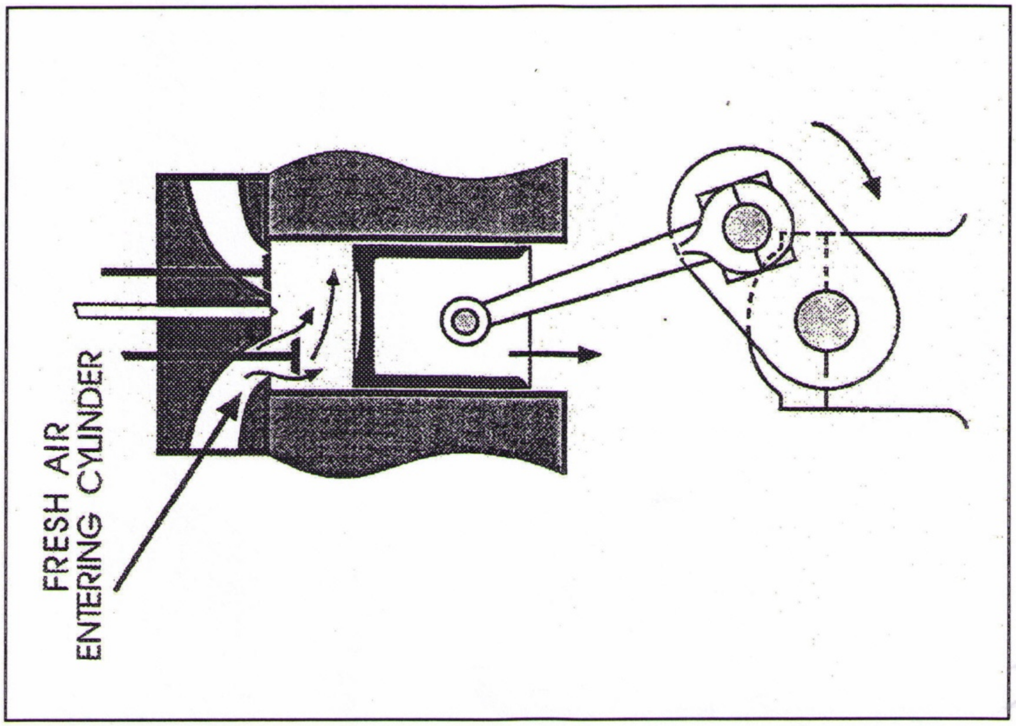

Figure 2-8 Intake Air Charge

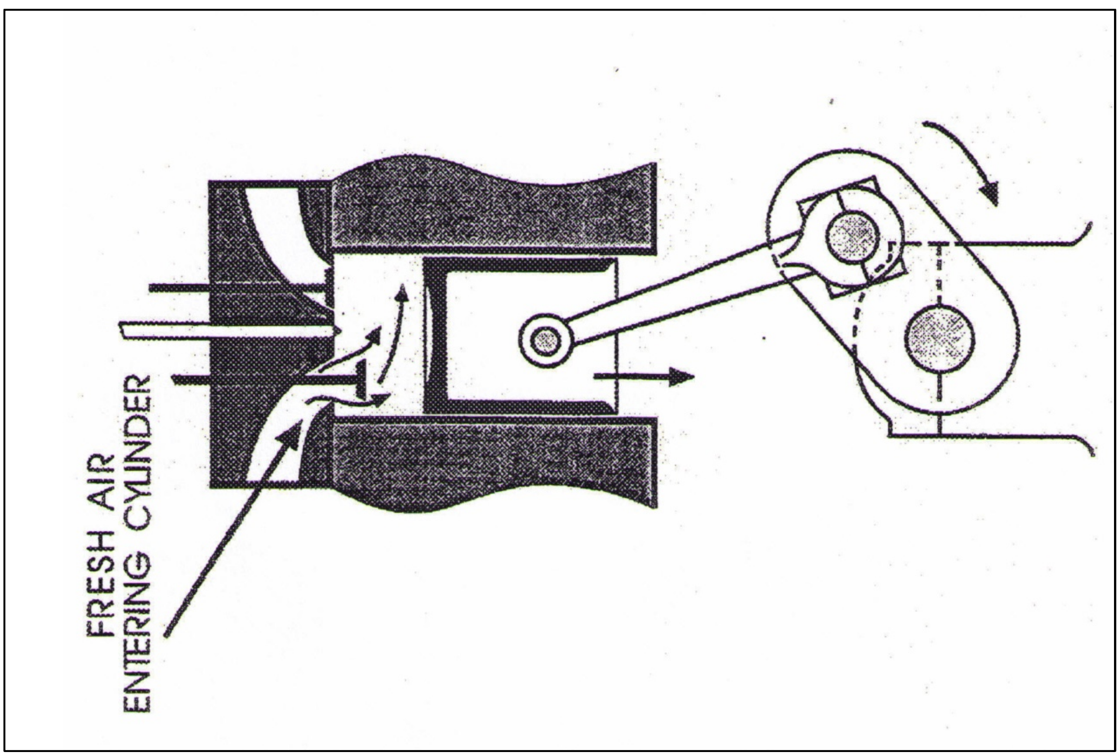

Figure 2-9 Compression of Air Charge

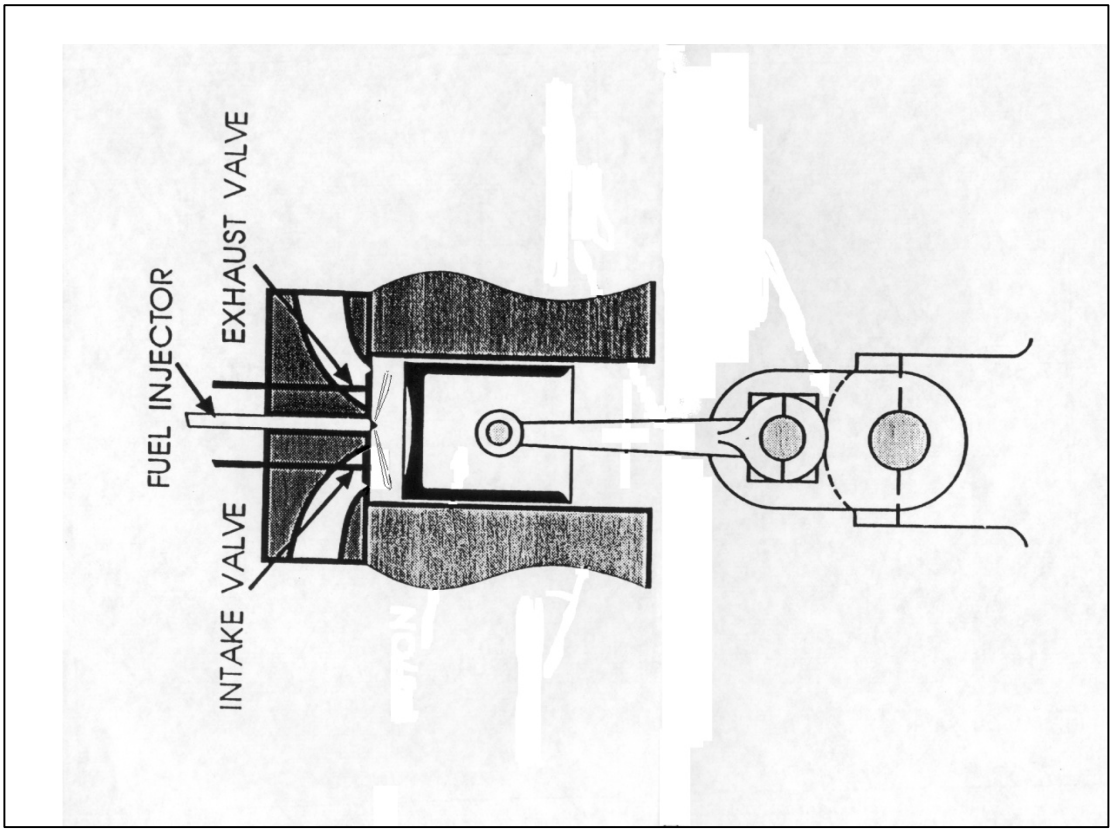

Figure 2-10 Injection of Fuel

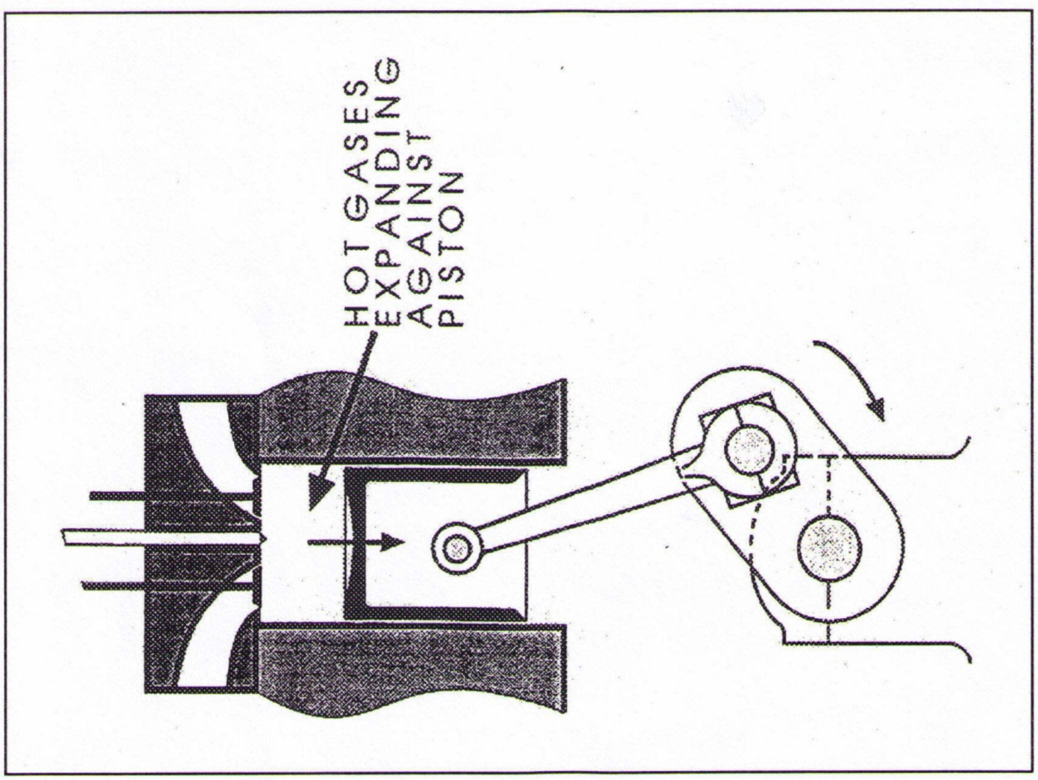

Figure 2-11 Development of Power

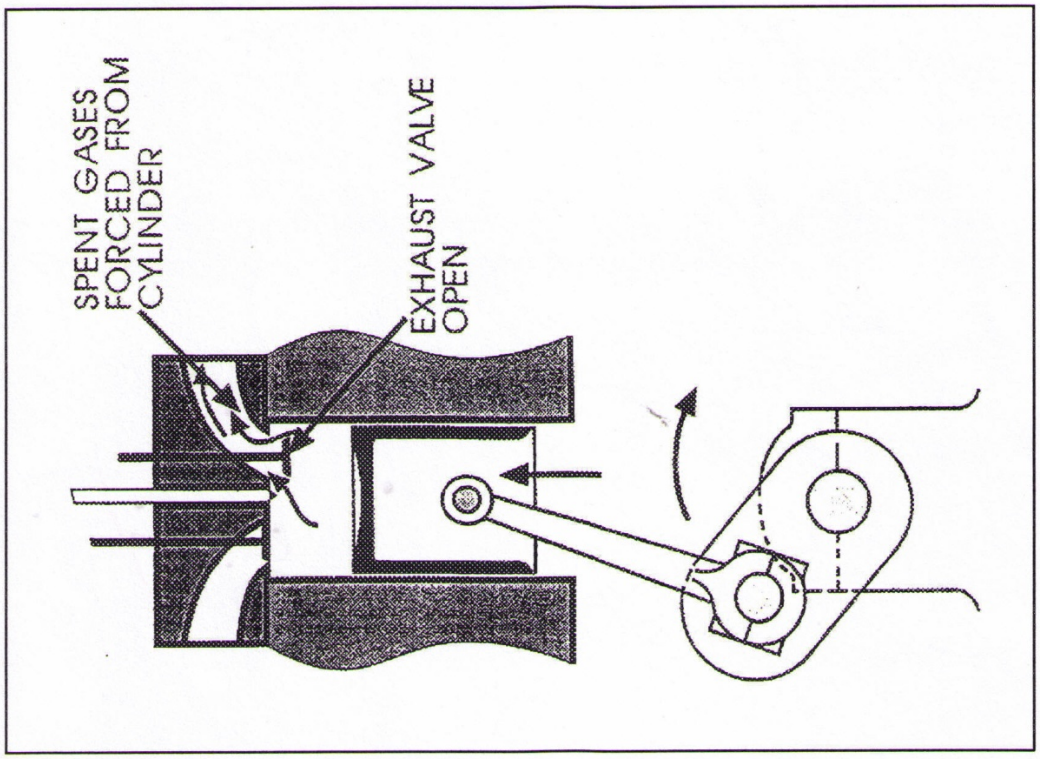

Figure 2-12 Exhaust of Spent Gases

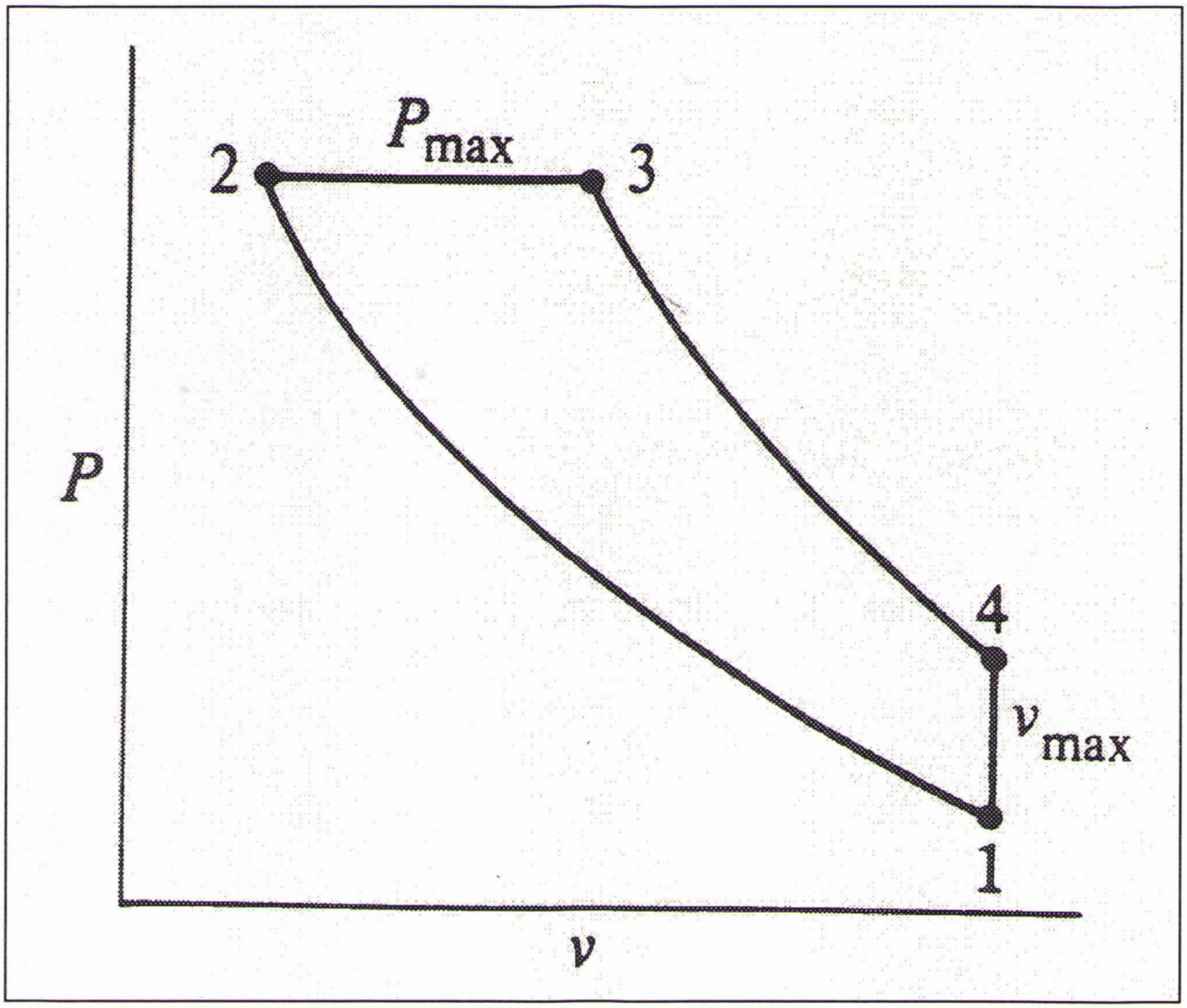

Figure 2-13 Air Standard Diesel Cycle

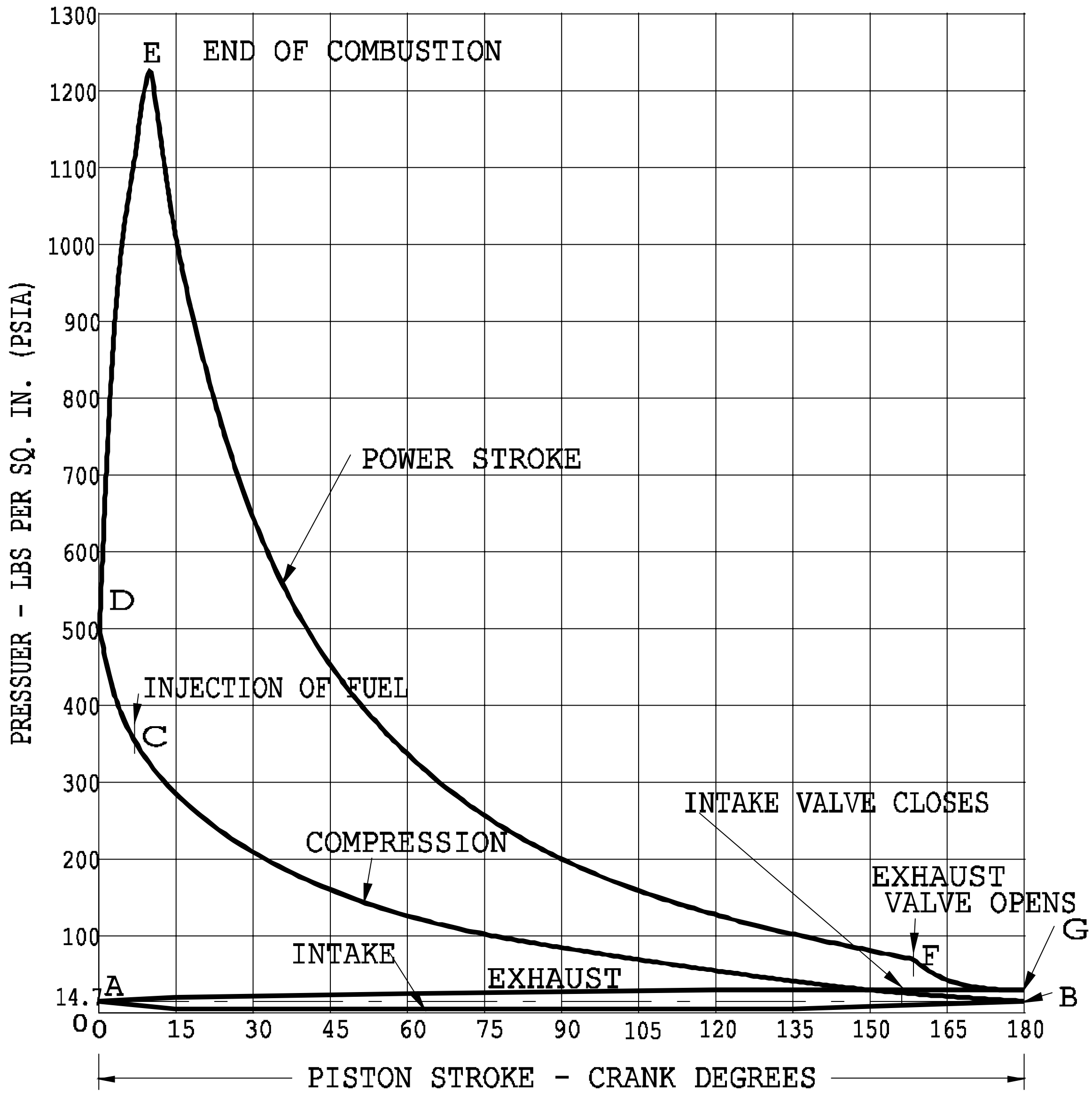

Figure 2-14 Pressure vs Stroke Diagram

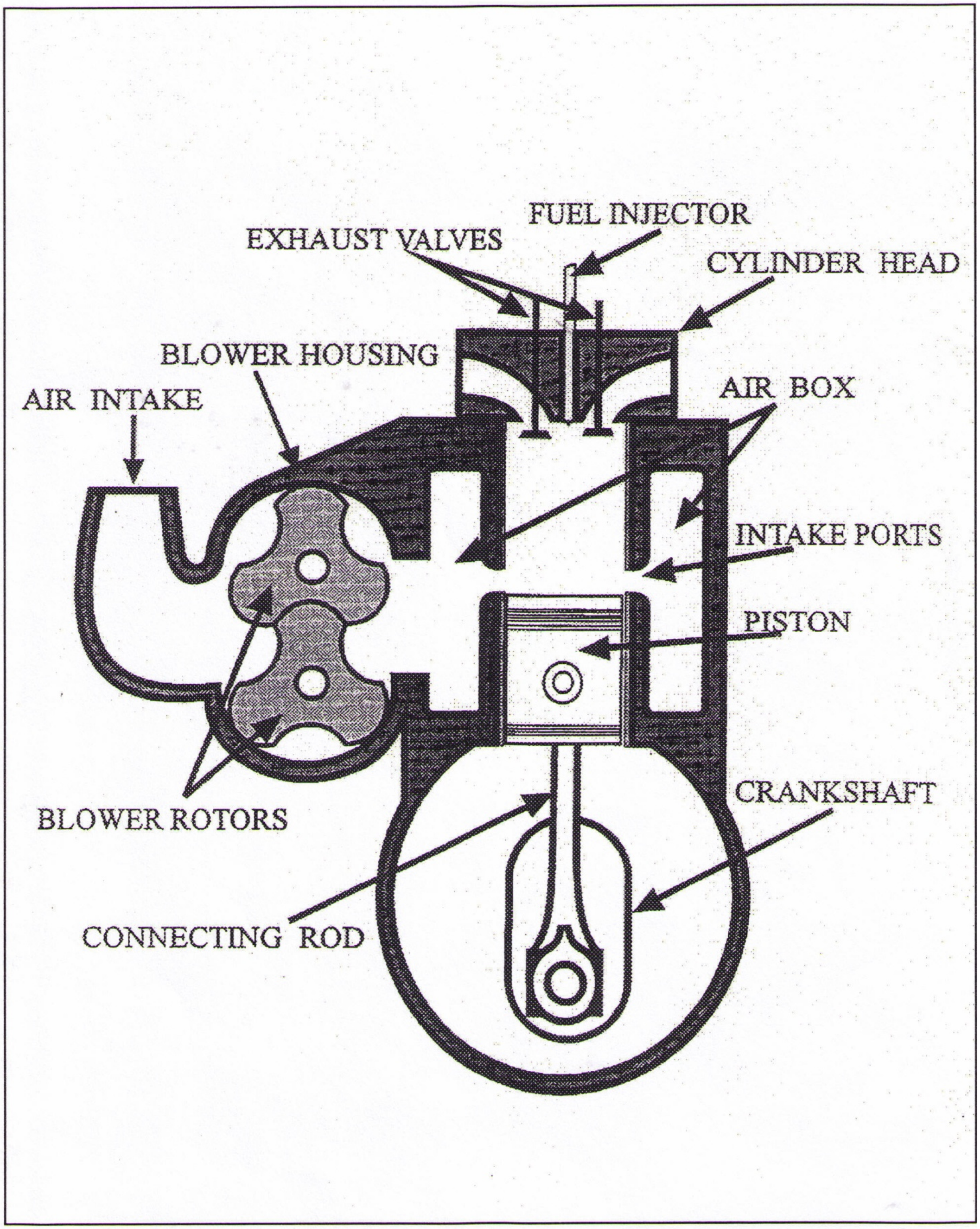

Figure 2-15 Cylinder Configuration – 2-Stroke Cycle EMD Engine

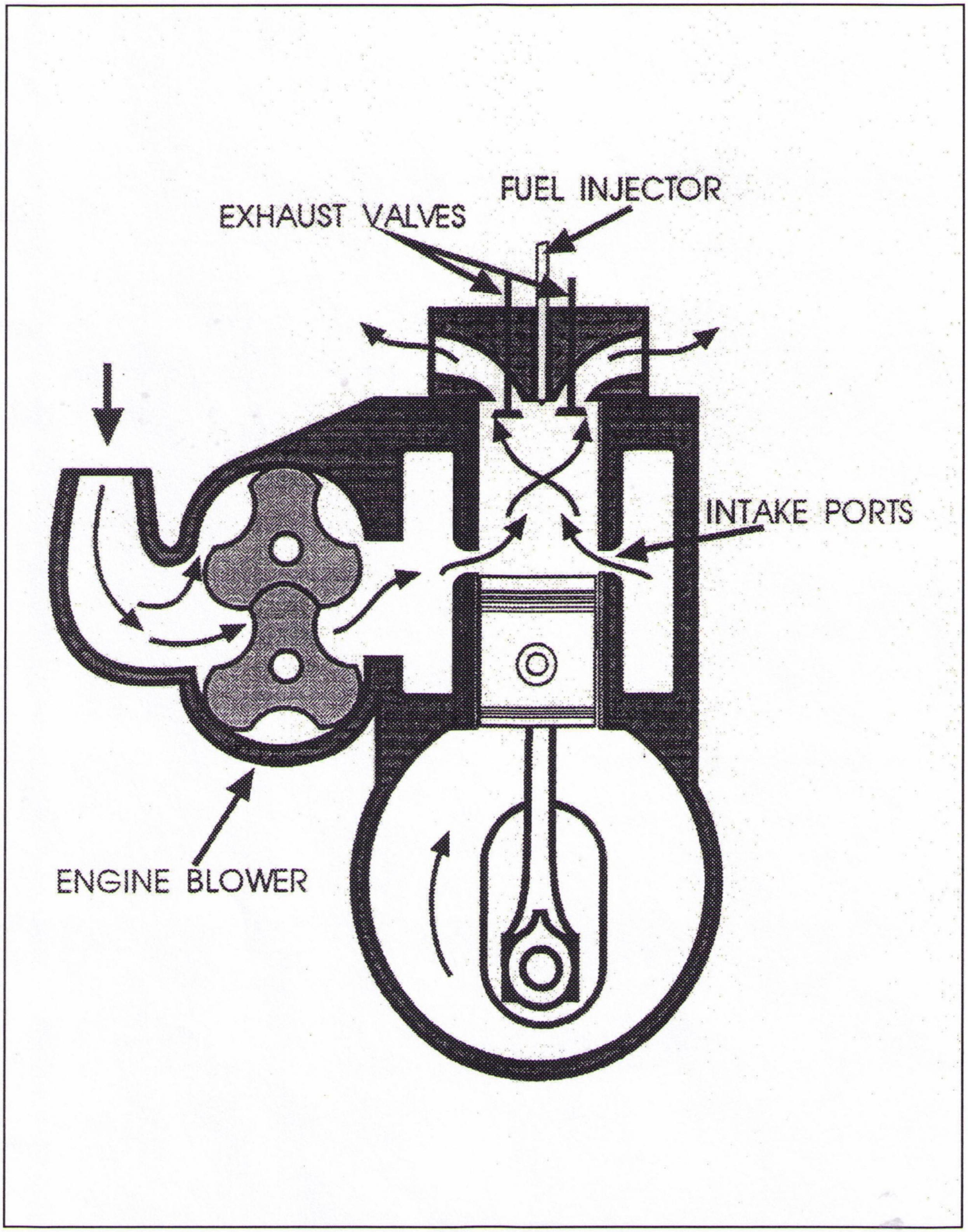

Figure 2-16 Intake Event

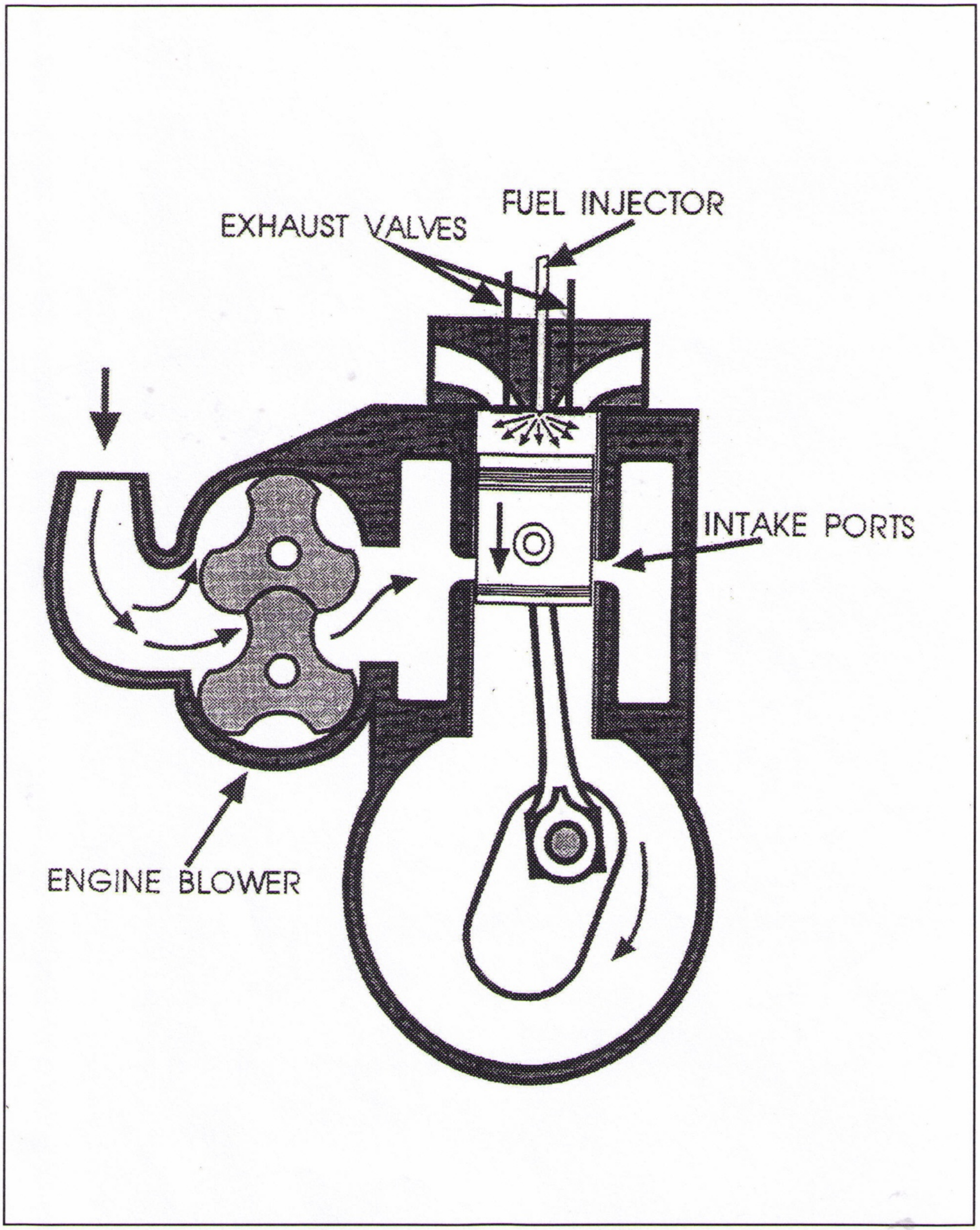

Figure 2-17 Compression Event

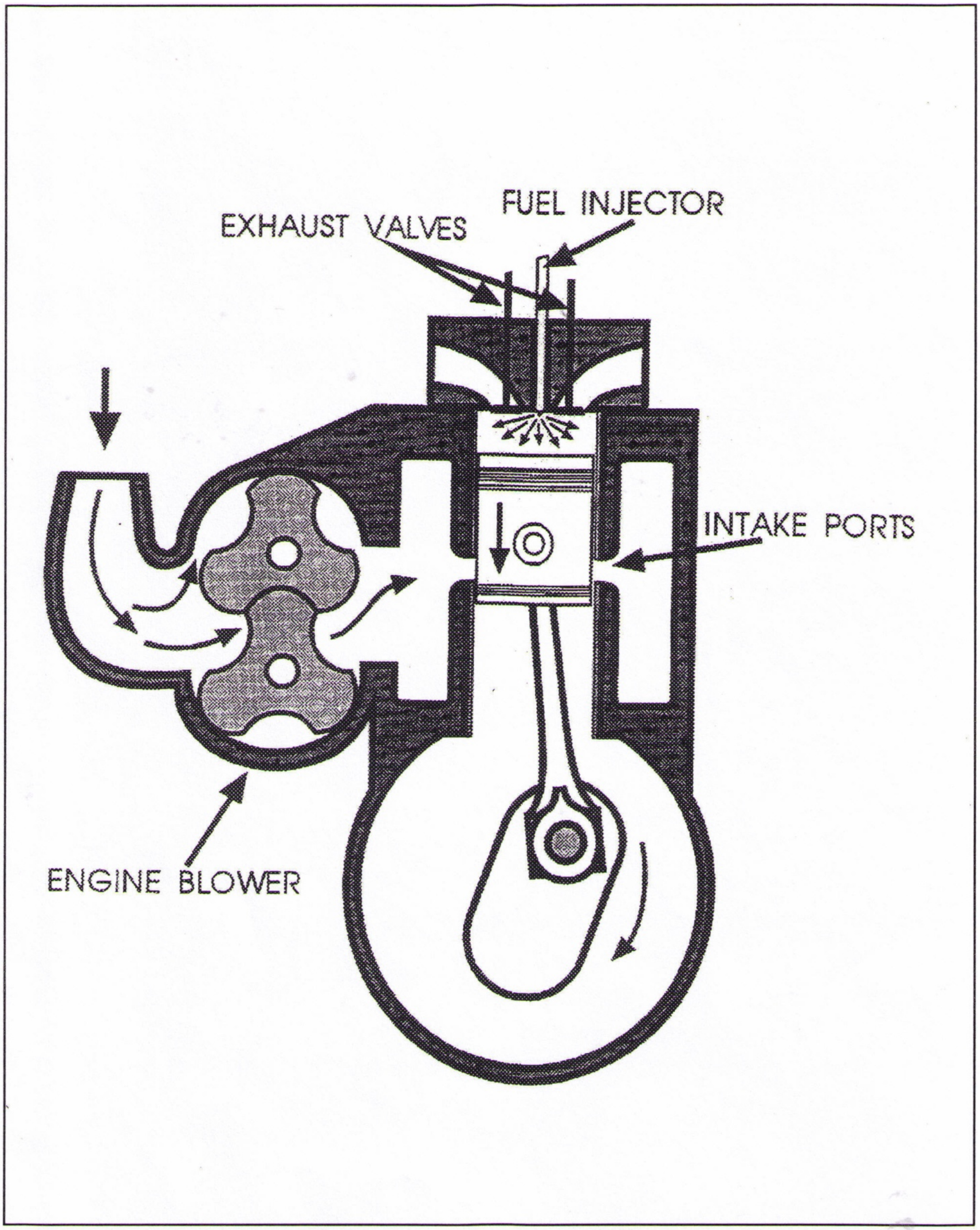

Figure 2-18 Combustion and Power Stroke

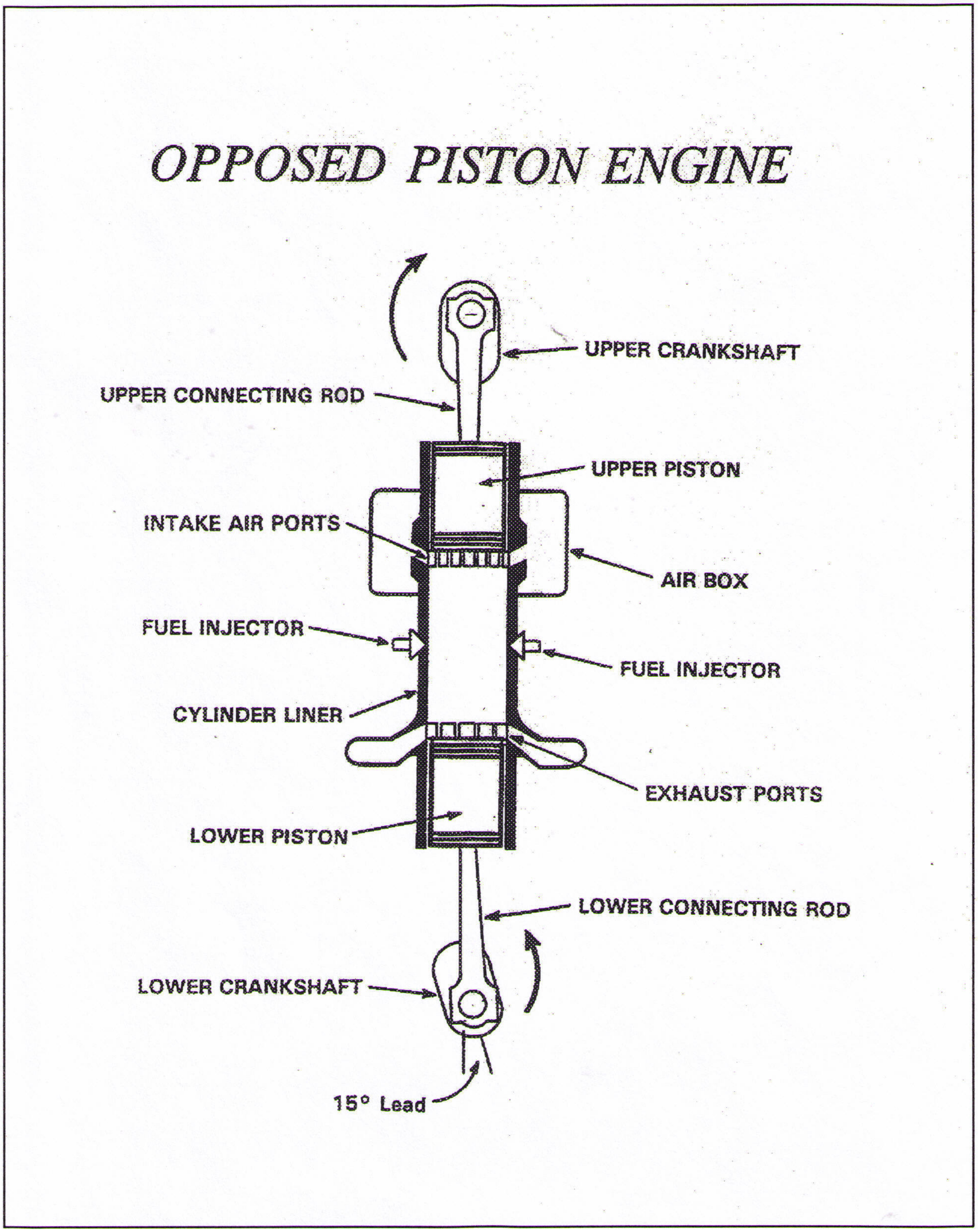

Figure 2-19 Cylinder Configuration – 2-Stroke Cycle OP Engine

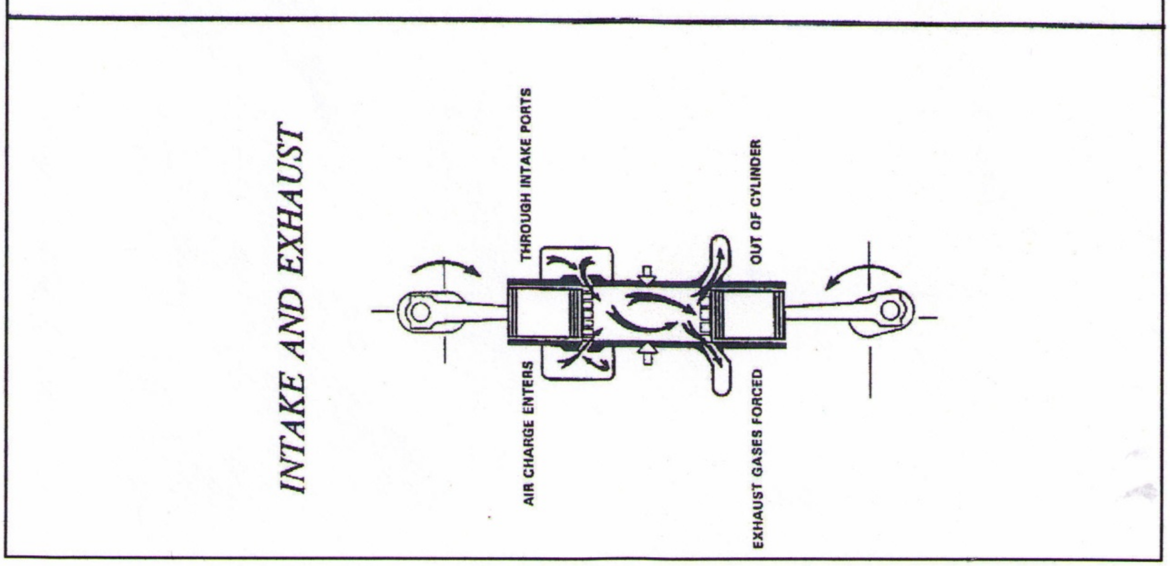

Figure 2-20 Intake Event

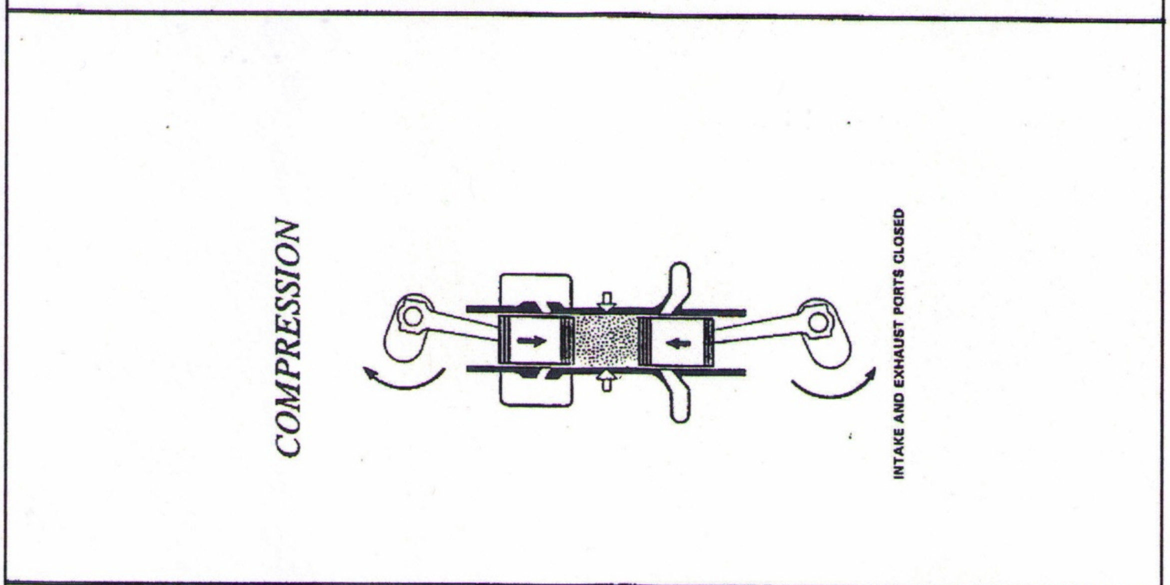

Figure 2-21 Compression Event

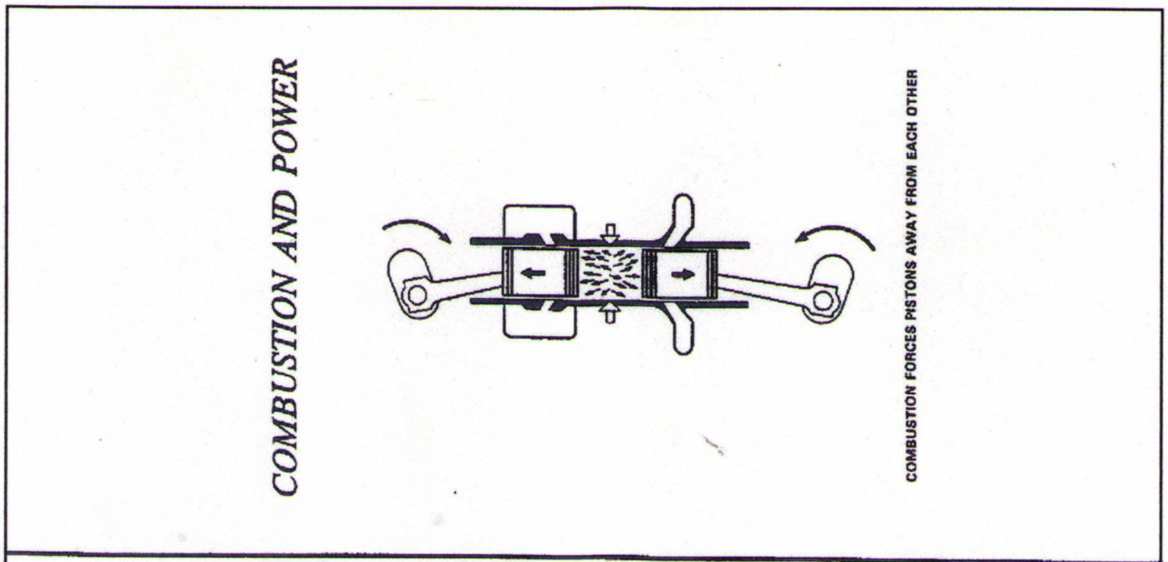

Figure 2-22 Combustion & Power

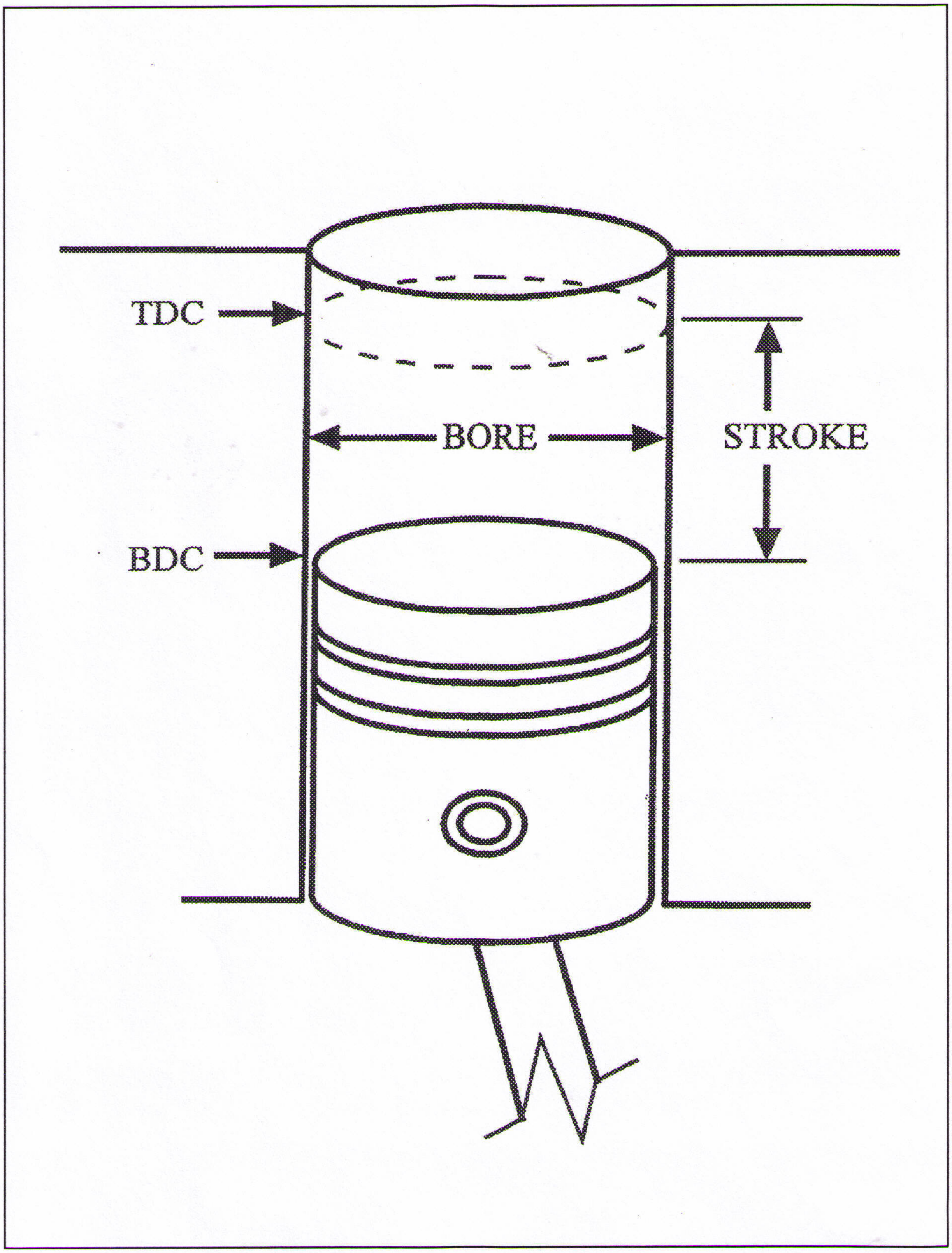

Figure 2-23 Bore & Stroke

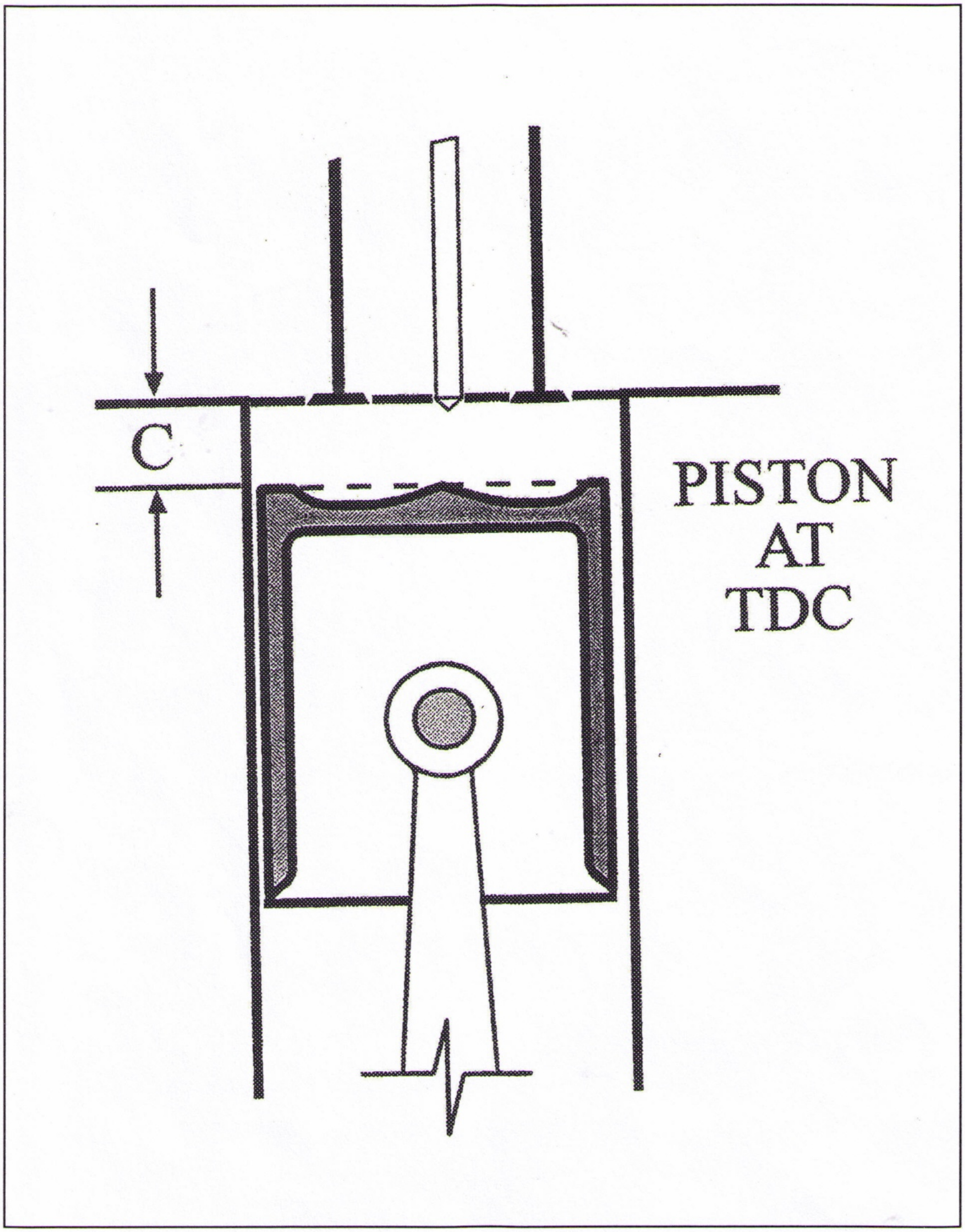

Figure 2-24 Clearance Volume

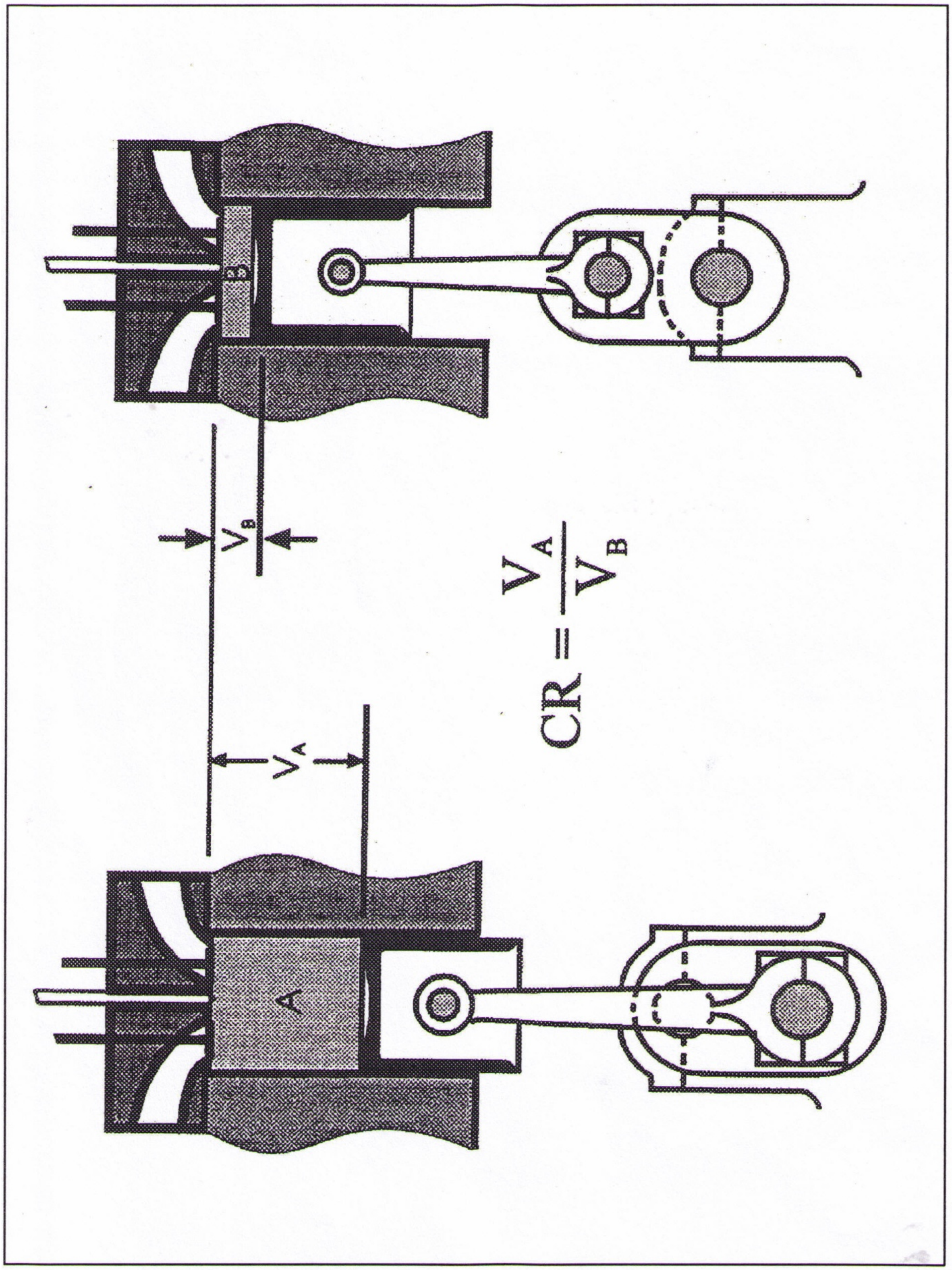

Figure 2-25 Compression Ratio

Event	2-Cycle Engines Fraction of a Second	4-Cycle Engines Fraction of a Second
Fuel Injection	.003	.003
Power	.022	.026
Exhaust	.005	.031
Scavenging	.018	.022
Intake	.002	.033
Compression	.020	.025

The above figures are based on an engine operating at 900 rpm. For a 2-cycle engine, all events must occur within one revolution or .067 seconds. For the 4-cycle engine, there is twice as much time.

Note: Some events overlap; therefore, not all figures are cumulative.

Figure 2-26 Typical Times for Events 900 rpm Diesel

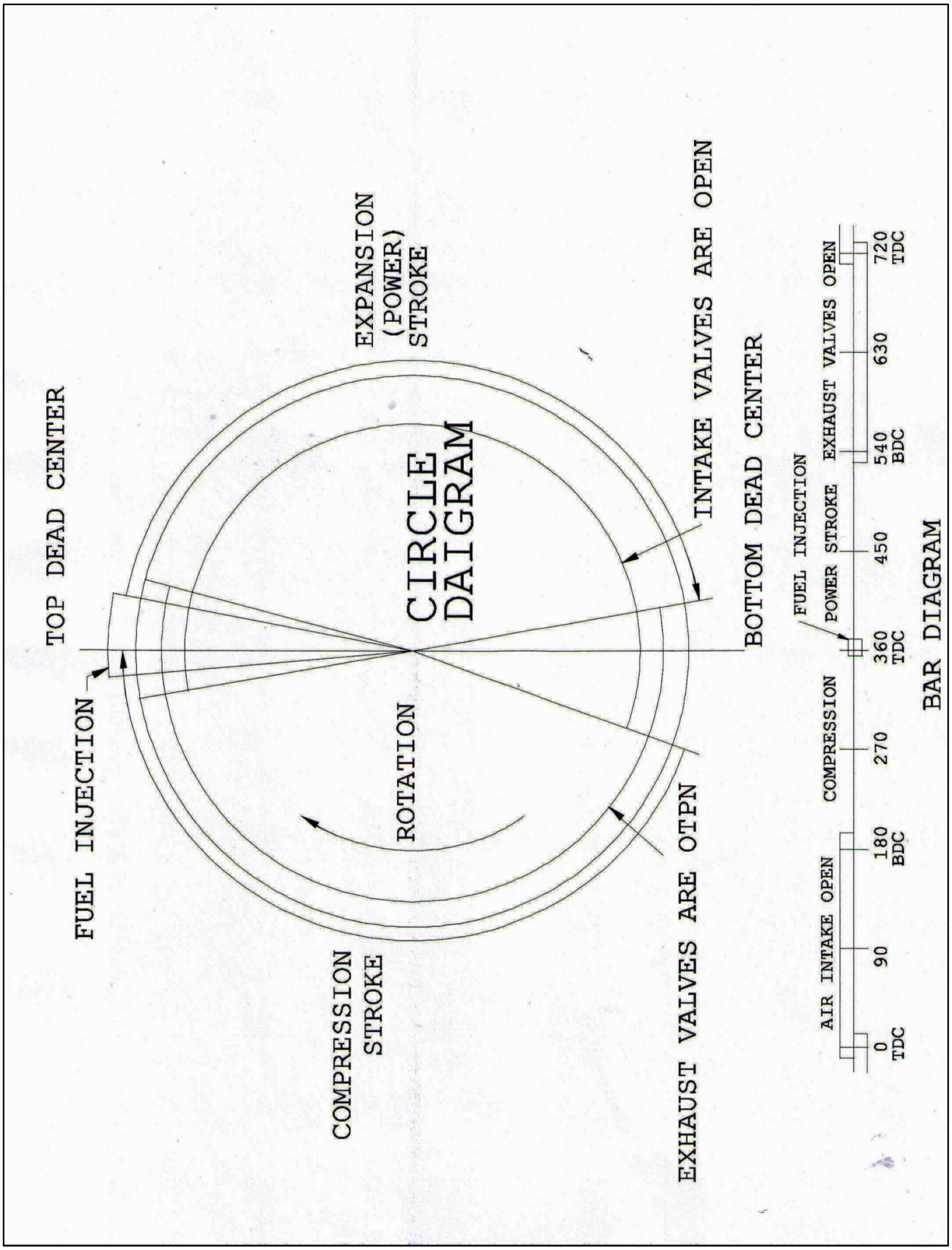

Figure 2-27A Typical Timing Diagram 4-Stroke Cycle

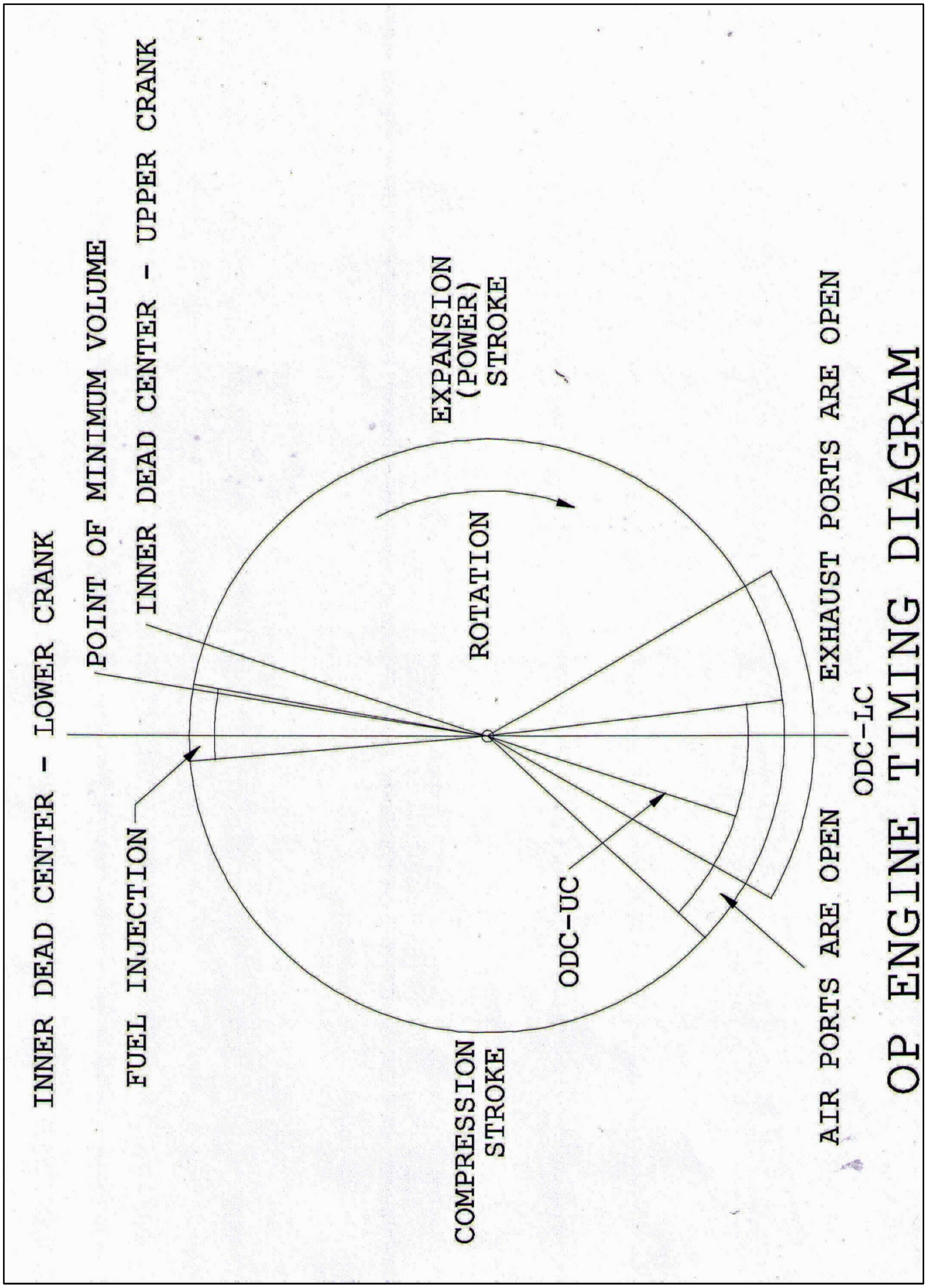

Figure 2-27B Typical Timing Diagram 2-Stroke Cycle

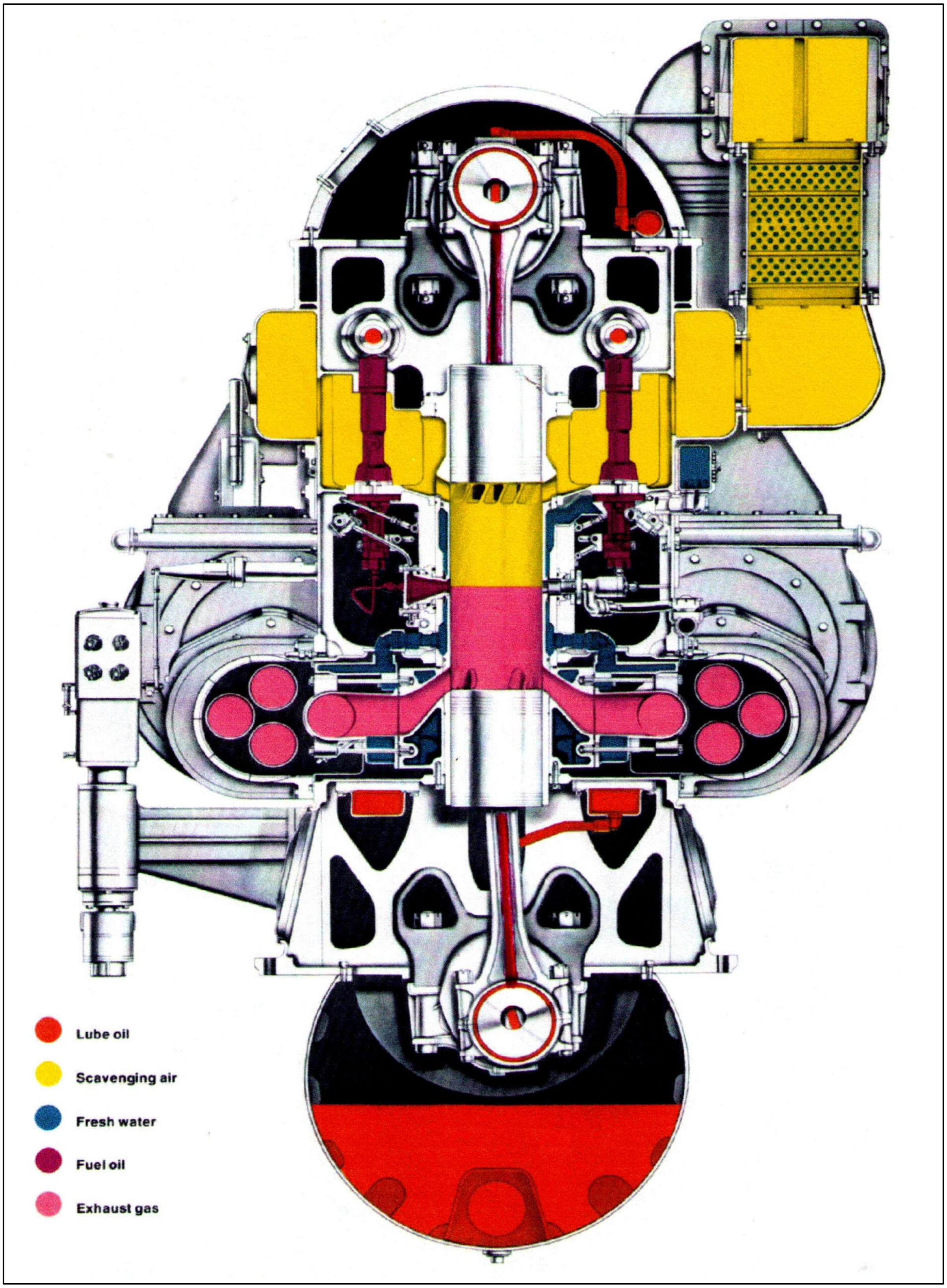

Figure 2-28 OP Engine Cross Section

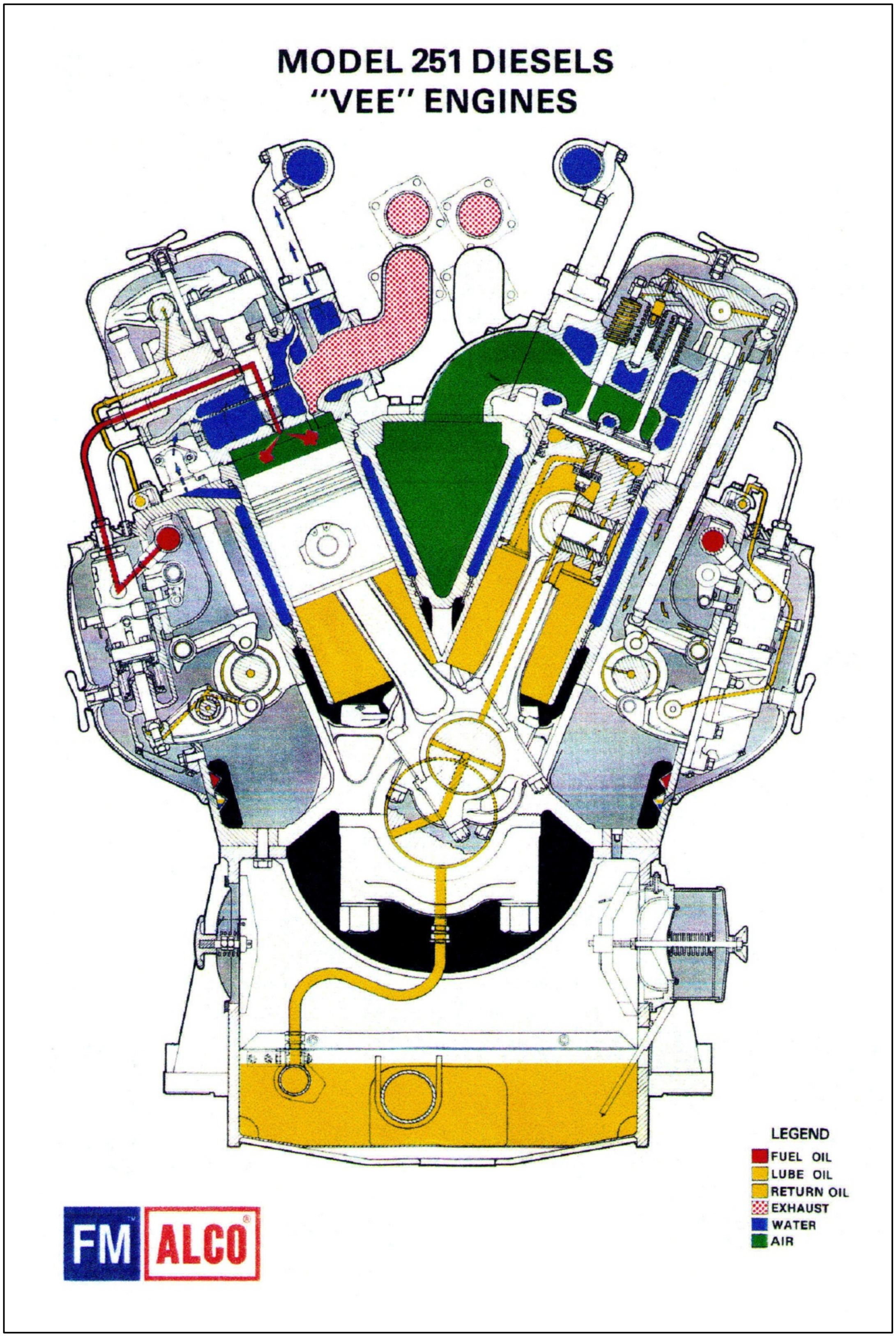

Figure 2-29 ALCO Engine Cross Section

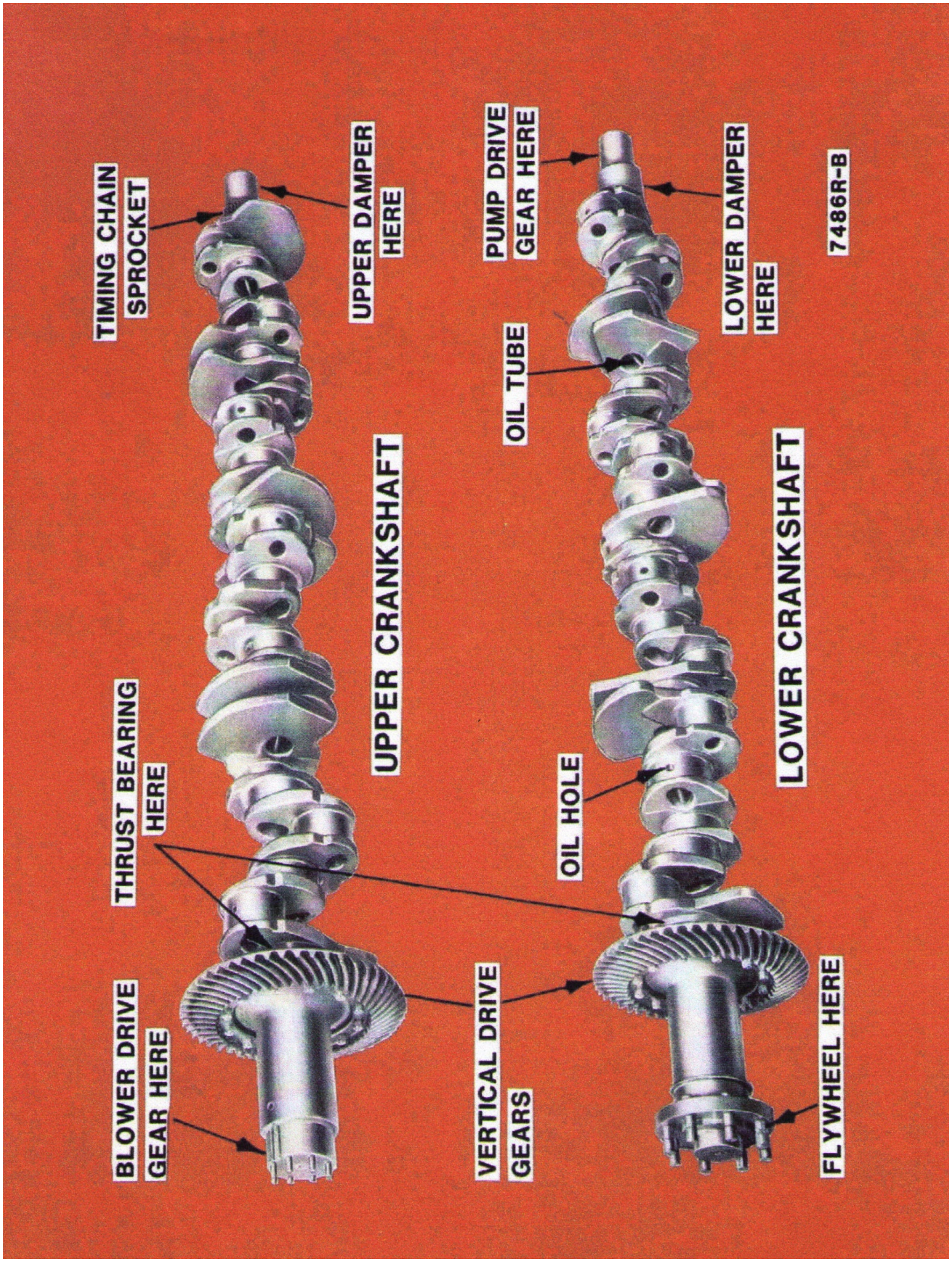

Figure 2-30 OP Engine Crankshaft

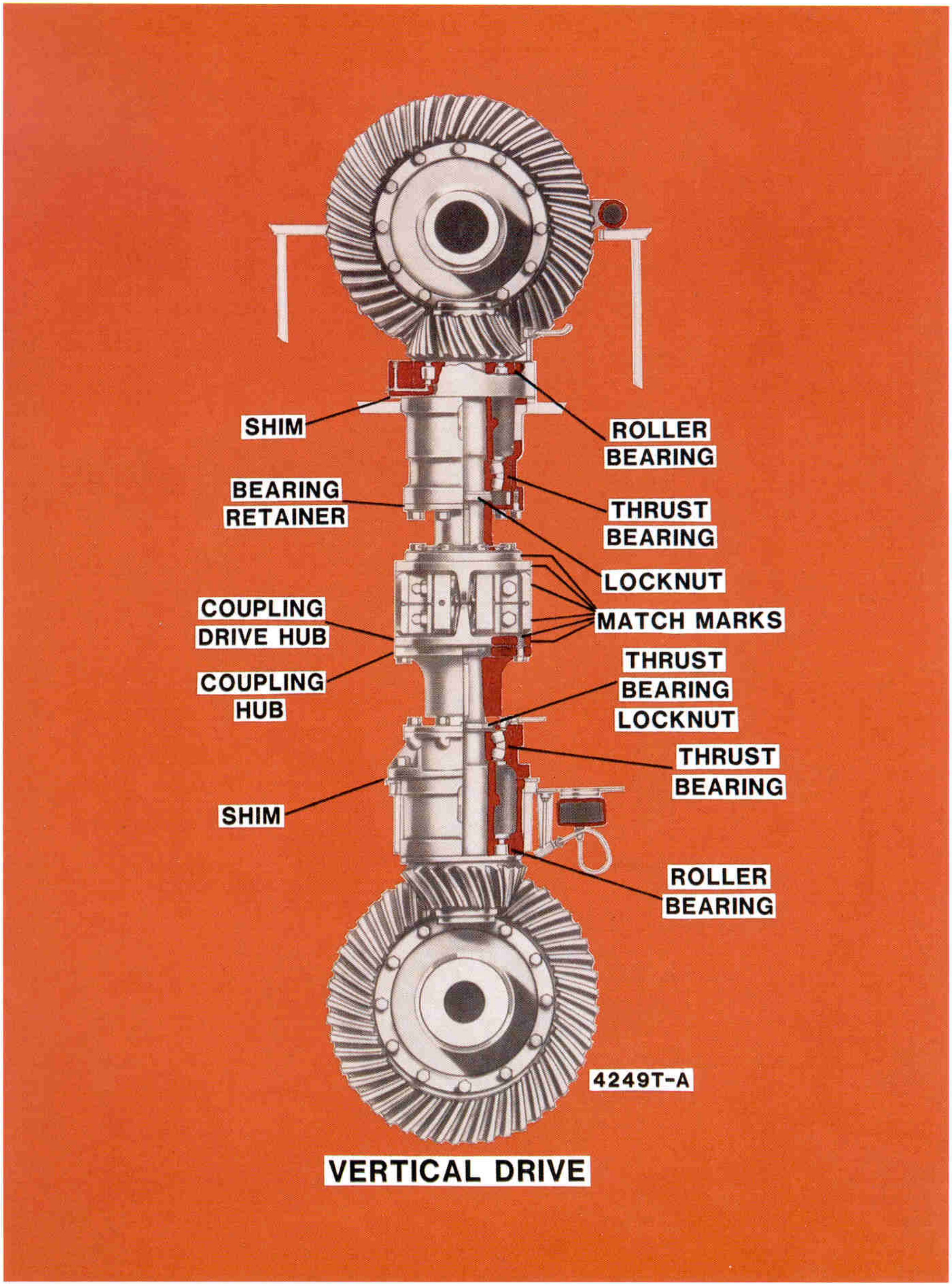

Figure 2-31 OP Engine Vertical Drive

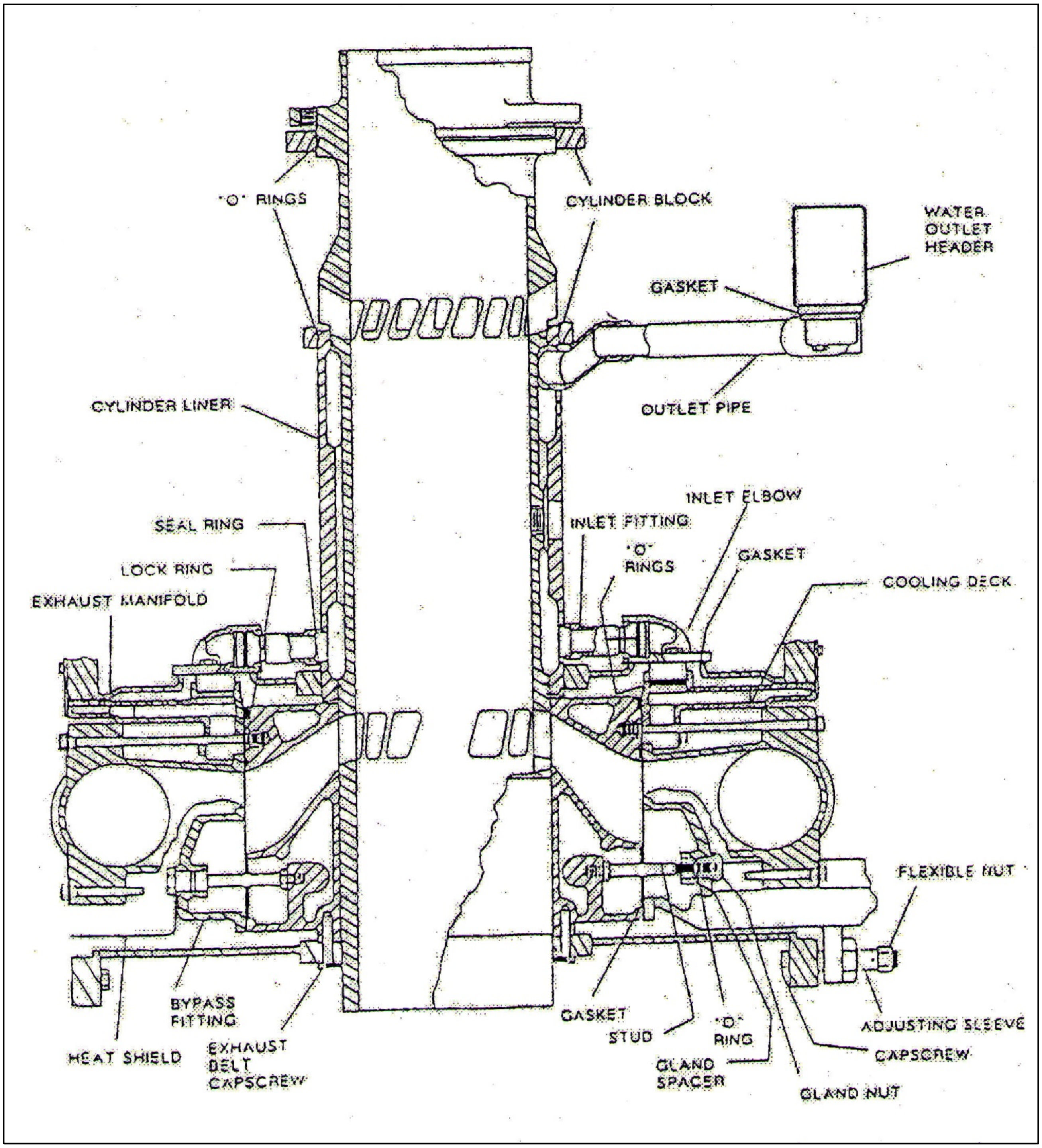

Figure 2-32 Cylinder Liner Jacket Water Cooling

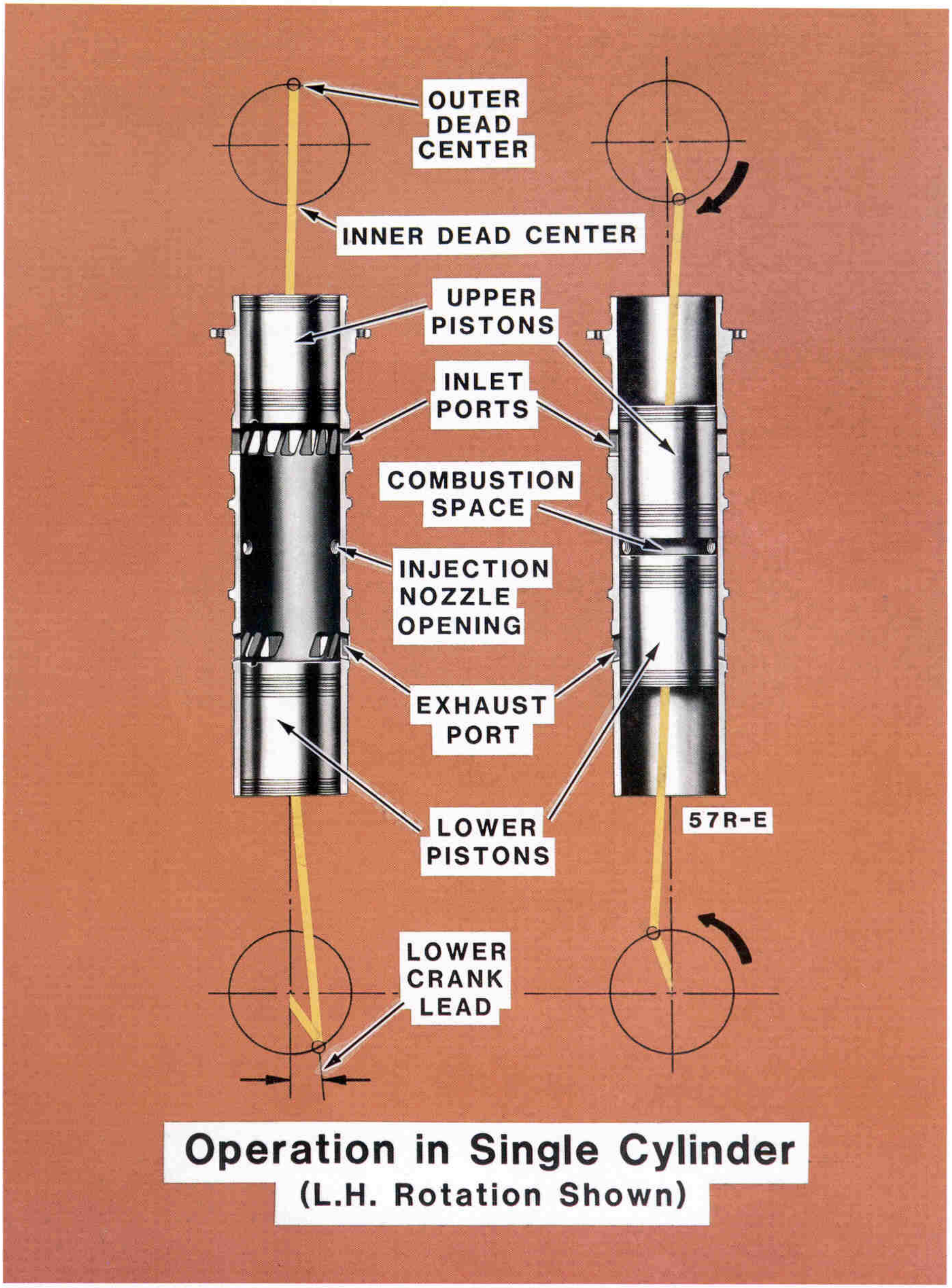

Figure 2-33 OP Engine Cylinder

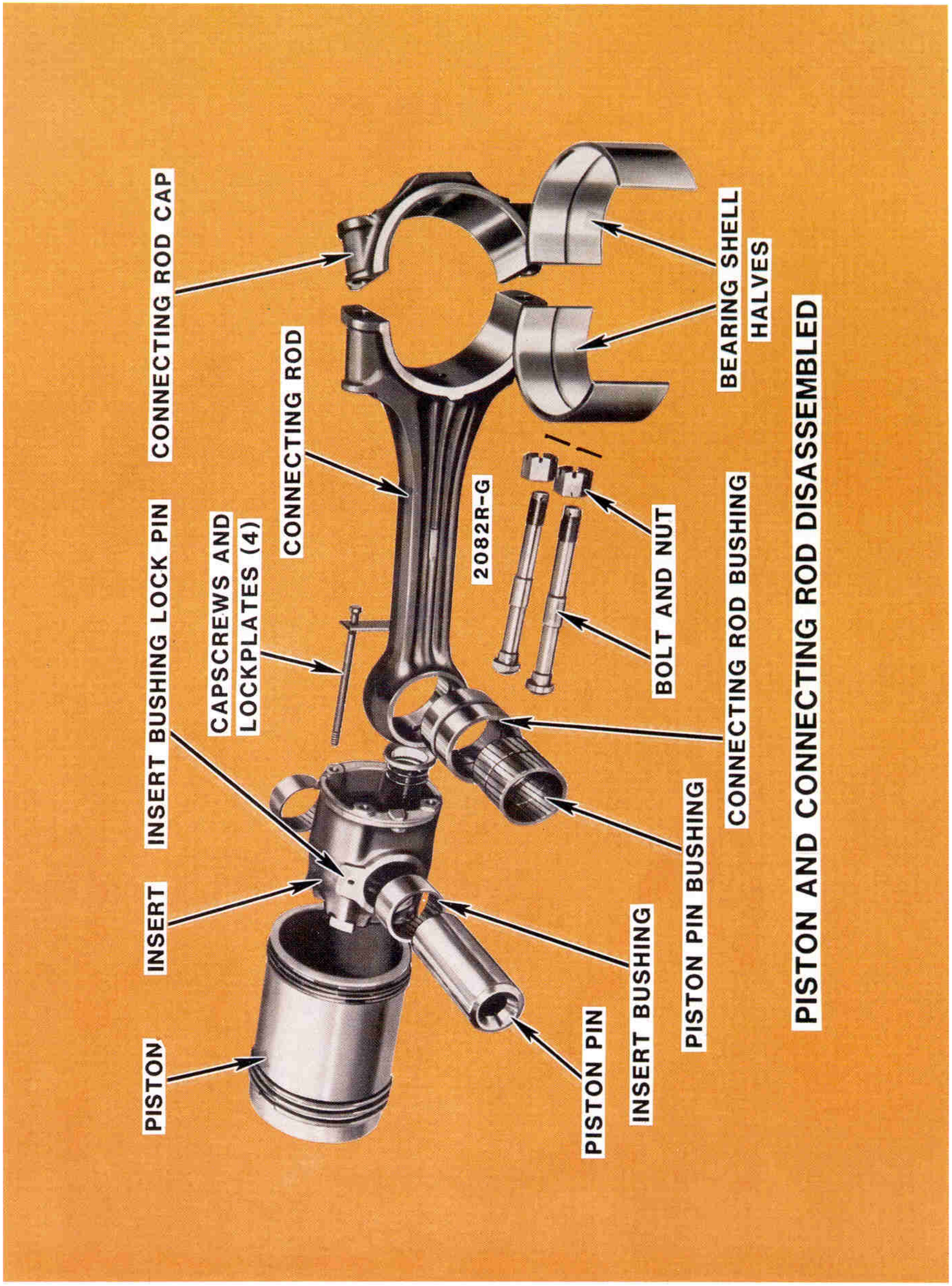

Figure 2-34 OP Piston and Con-Rod Assembly

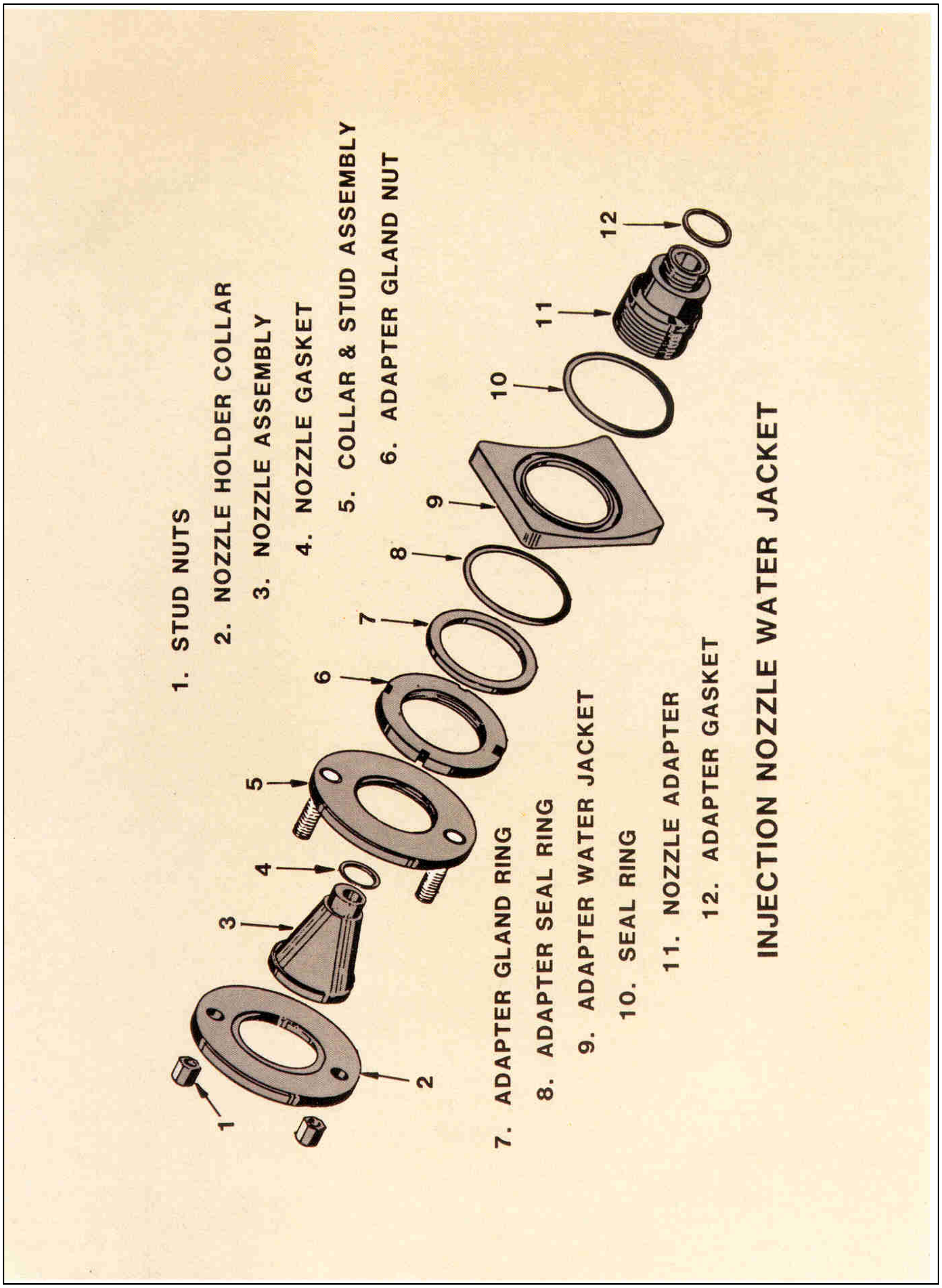

Figure 2-35 OP Injection Nozzle Mounting

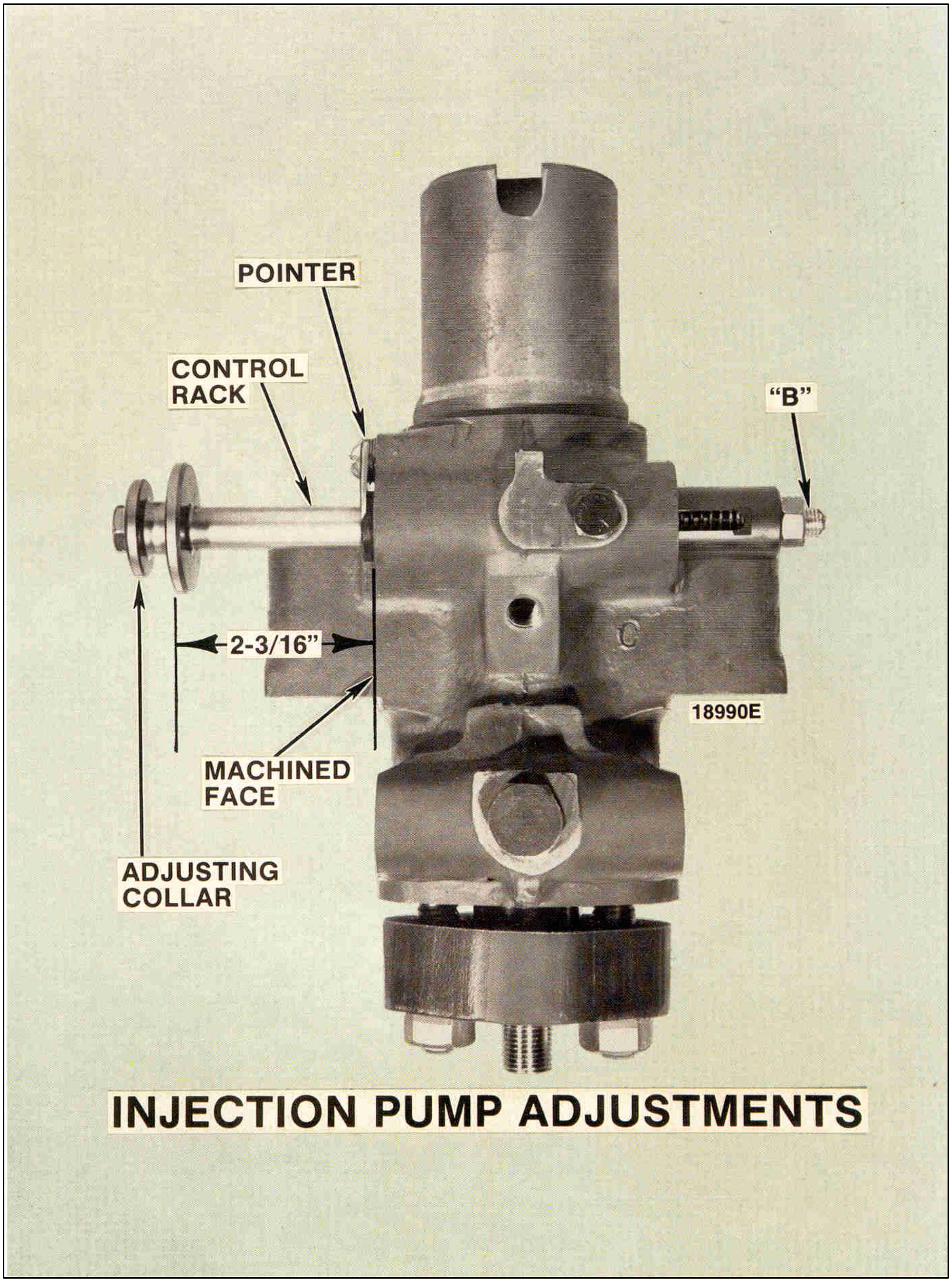

Figure 2-36 OP Fuel Injection Pump

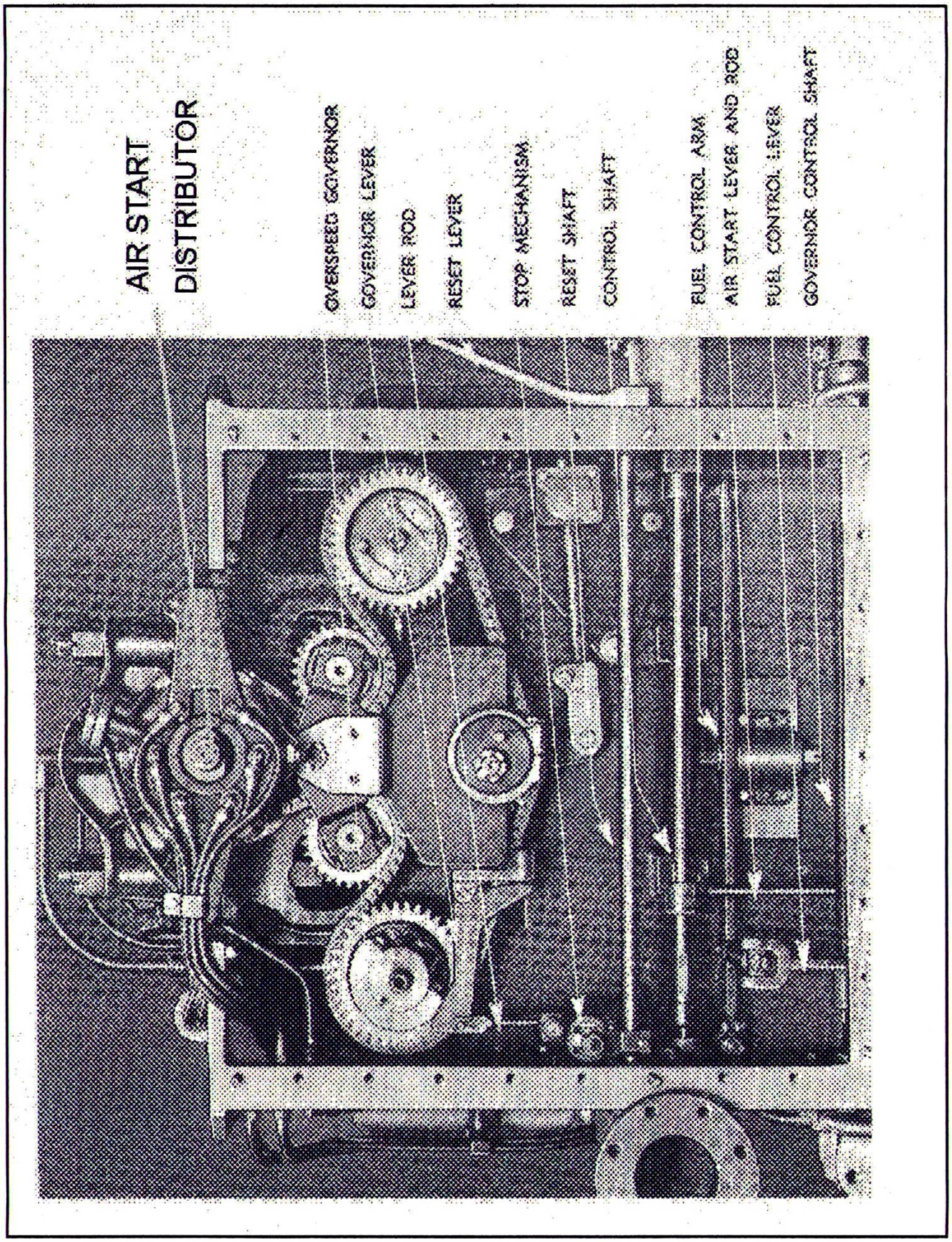

Figure 2-37 Chain Type Drive Mechanism

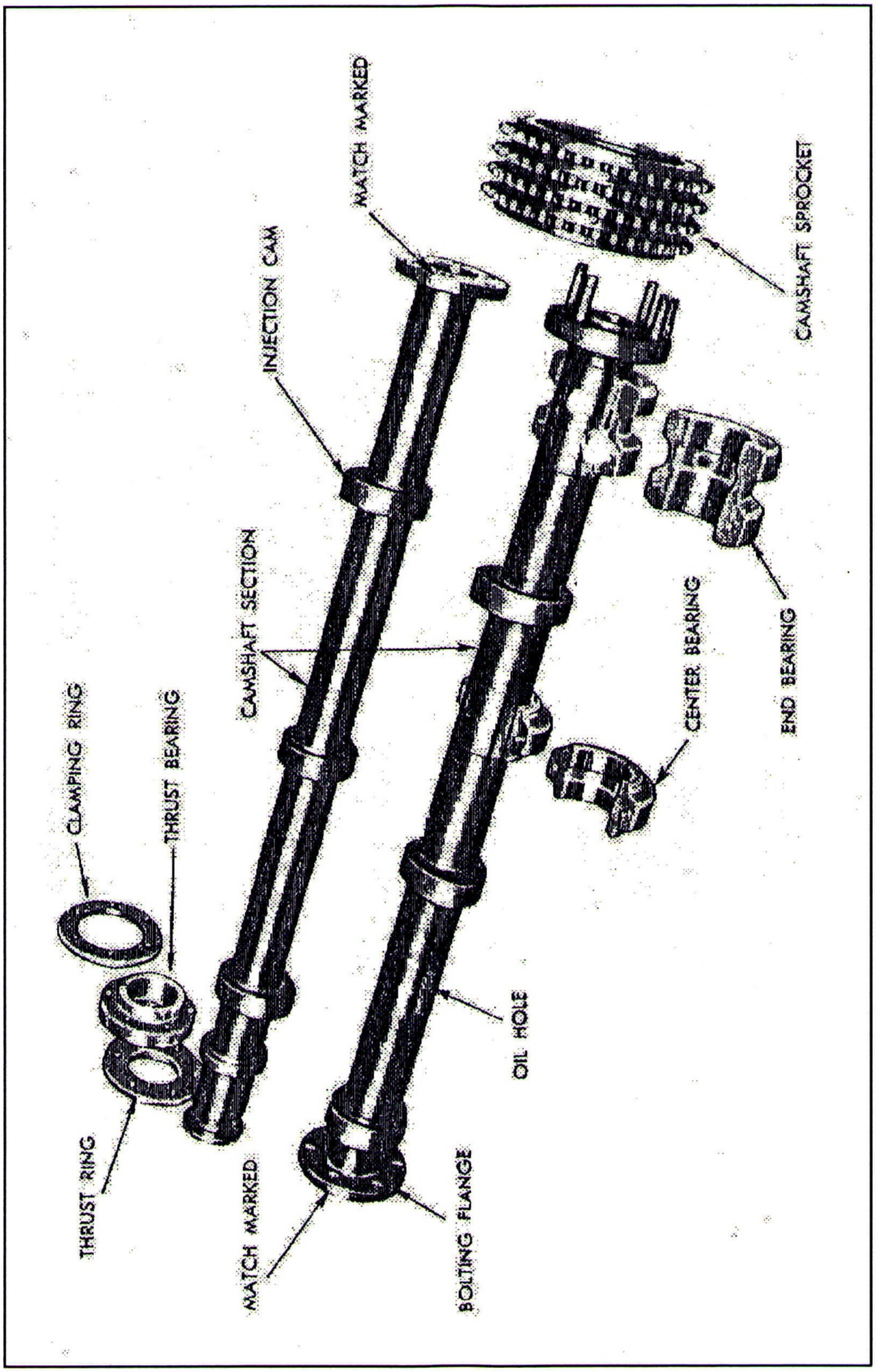

Figure 2-38 Camshaft Control End

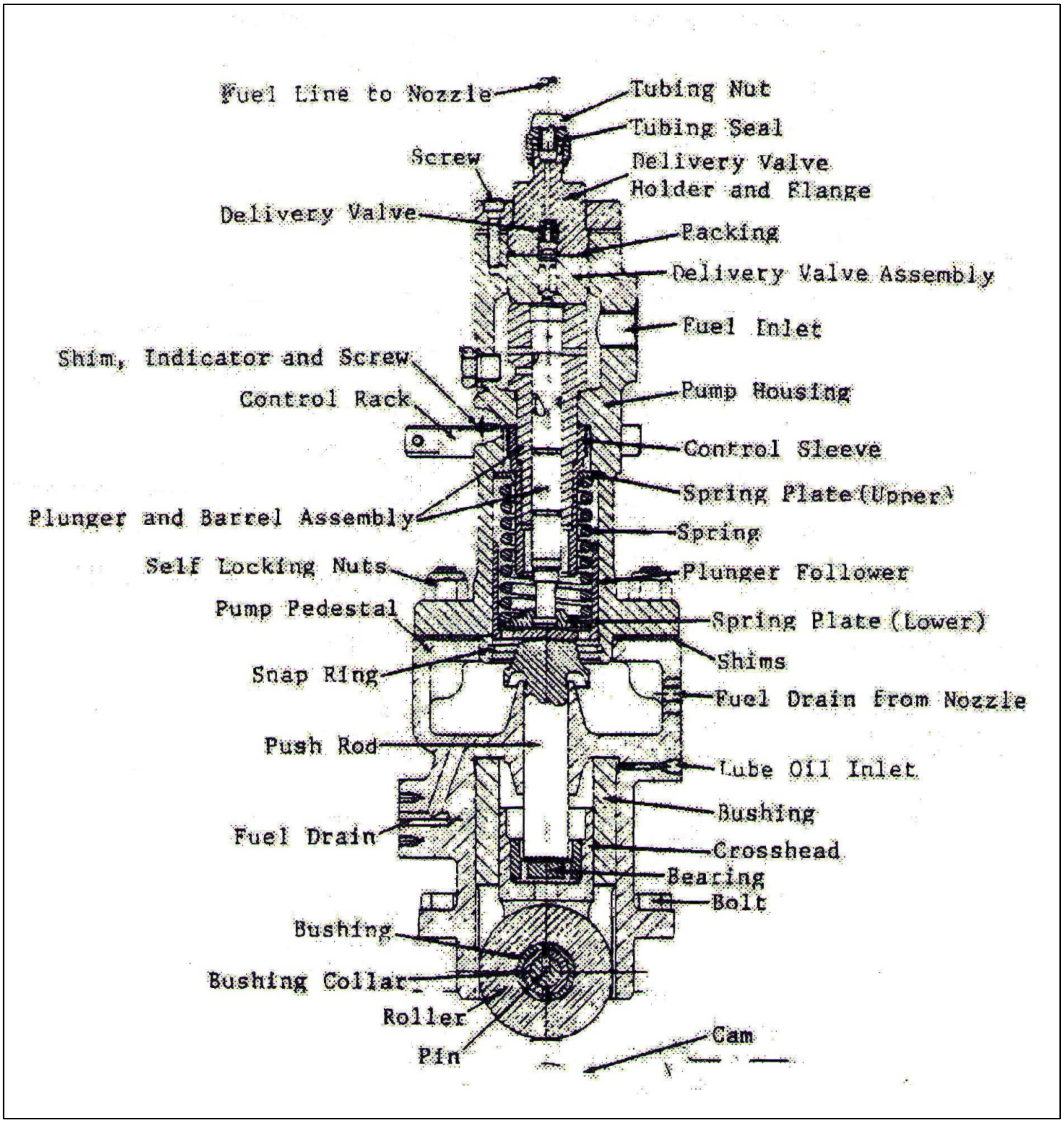

Figure 2-39 Fuel Injection Assembly

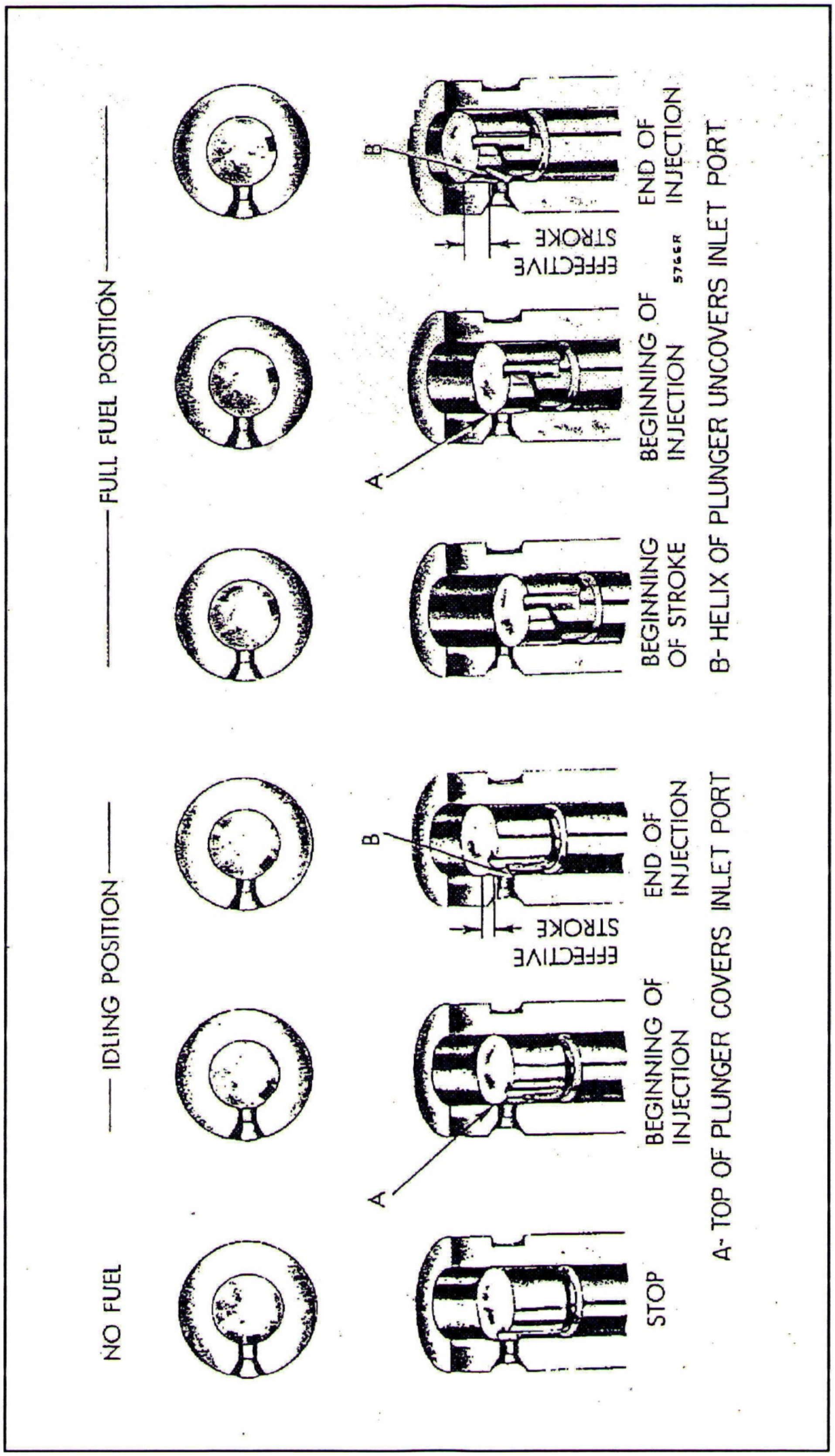

Figure 2-40 Injection Pump Plunger Positions

HANDS-ON SESSION 1

1.0 DETAILED PRESENTATION OF THE 2-STROKE CYCLE OP AND 4-STROKE CYCLE ALCO ENGINES

Purpose

The overall purpose of this session is for the students to identify engine components, engine systems, and how they operate as the engine goes through all of its cycles of operation.

Leaning Objectives

As a result of this lesson, you will be able to:

1. Identify the major features of the 2-stroke cycle OP engine and of the 4-stroke cycle ALCO engine.

2. Identify the primary systems and components of the OP and ALCO engines.

3. Understand the functions of the major features, primary systems, and major components of the OP and ALCO engines.

4. Operate the rotatable cutaways for self-learning.

1.1 OP Engine Rotatable Cutaway Explanation

The OP Cutaway engine will be used to demonstrate features and characteristics of this 2-stroke cycle engine. Figure 2-28 shows a cross sectional view of this engine design. It has two crankshafts–an upper crankshaft housed and supported in the top of the engine and a lower crankshaft housed and supported in the lower end of the cylinder block–in the crankcase. See Figure 2-30. The two crankshafts are joined together at the back (power) end of the engine by a vertical drive shaft which is connected to the two crankshafts by bevel (miter) gear sets. See Figure 2-31.

The crankshafts rotate at the same speed but in opposite directions, and they are offset by a number of rotational degrees. The lower shaft leads the upper shaft a few degrees. This difference in angular position is called the ‘crank lead’. As the crankshafts rotate, the pistons travel up and down in the engine cylinders. The cylinder walls have intake air and exhaust ports. The combustion chamber is formed by the walls of the cylinder and the crowns (tops) of the pistons. See Figures 2-32 and 2-33. Neither conventional cylinder heads nor valves are used in this engine.

Throughout the following discussion, refer to Figure 2-33. The two cycles of this engine begin when air is admitted to the cylinders through their ports when the upper piston nears outer dead center (ODC). Air is supplied to the area around the intake ports by pressurized air supplied either by the scavenging air blower (non-turbo engines) or by the turbocharger and blower on turbo-charged engines. At the very outward position of the upper piston, the exhaust ports are also open. Fresh intake air is forced down through the cylinder and out the exhaust ports. This scavenges the exhaust gases from the last cycle. Because the air and exhaust ports are open simultaneously, the fresh air blows completely through the cylinder in one direction. This is called ‘uniflow’ scavenging.

In a few more degrees of crankshaft rotation, the exhaust ports are covered by the lower piston, and the fresh air 'super charges' the cylinder space to inlet air manifold pressure. As the crankshaft continues to rotate, the air ports also close. From this point on, the air is compressed as the two pistons approach each other. As the air is compressed, its pressure and temperature increase.

A few degrees before the lower piston arrives at its inner dead center (IDC) position, fuel is injected into the cylinder through the two injection nozzles. The injection nozzles spray fuel under high pressure into the cylinder through holes in the side wall of the cylinder liner assembly. The fuel heated by the hot air in the cylinder gets to its ignition temperature of about 450 to 550^{o}F. Some of the fuel ignites and begins to burn. This raises the temperature further until soon all of the fuel is burning as it mixes with the oxygen in the air in the cylinder.

By the time the fuel is burning well and the pistons have traveled beyond their IDC positions, combustion pressure on the pistons and connecting rods create the force to rotate the crankshafts. This is the power stroke of the engine. In order for the engine to run smoothly, there must be several cylinders that fire in sequence and are timed throughout a revolution of the crankshaft. Each cylinder contributes to generating power that is used for first, producing the power necessary for the compression taking place in other cylinders, second, to overcome the friction within the engine, and lastly, to produce power to drive the generator.

As the pistons travel toward (ODC), the pressure and temperature in the cylinders decrease as the pistons are driven apart and cylinder volume increases. When the pistons approach ODC, the lower piston uncovers the exhaust ports. The cylinder pressure is further reduced as the exhaust gases leave the cylinder. If the engine is turbocharged, the pressurized high temperature exhaust gases provide the power to drive the turbocharger.

As the crankshaft continues its rotation, the air ports are uncovered, allowing air to enter the cylinder and scavenge the exhaust gases from the cylinder. At this point, the engine has made one complete revolution of the crankshaft and each piston has made two strokes.

For further information on the cycle of the engine, see Figures 2-14 and 2-19 through 2-23.

1.1.1 Pistons and Piston Rings

The piston must have enough clearance to move freely up and down the cylinder bore both when it is hot and when it is cold. Therefore, there is clearance between the piston and the cylinder liner. Piston rings are provided to "seal off" the piston-to-liner space, thereby creating a combustion chamber without excessive blow-by. This is the purpose of the rings at the top of the piston, and they are called the compression rings. They are made slightly larger in diameter than the bore of the cylinder but have a gap to accommodate the expansion due to temperature changes. Usually there are multiple rings (3 or 4) as some combustion gasses will always bypass a single ring. With several rings, it is possible to get an almost perfect seal.

Another set of rings on the piston is for controlling the amount of lubrication that gets to the cylinder liner. In most engines, there is no specific supply of oil to the cylinder surface. The oil gets to the cylinder surface by being splashed or flailed there from the crankshaft and other rotating/oscillating parts. There is generally too much oil supplied by that means; therefore, it is necessary to have piston rings to control the amount of oil getting up into the space between the piston and the cylinder bore. Oil control rings generally have drain holes/slots. The piston is provided with drain holes in the control oil ring area to drain the excess oil back into the crankcase.

On 2-stroke cycle engines, particularly ported engines, it is necessary to also seal the crankcase from the lower end of the piston. This is done by putting the oil rings at the lower/upper end of the pistons shown in Figure 2-34.

The piston crowns on most large diesel engines are chrome plated. This protects the cast iron or steel piston crown material from the extreme heat of combustion in the cylinder.

1.1.2 Lube Oil Supply to the Piston

Lube oil from the crankcase is pumped through or around lube oil coolers to strainers/filters and then into the engine oil headers. On the OP engine, separate headers supply oil to the main bearings on the upper and lower crankshafts. Drilled passages from the main bearings feed the lube oil from the main bearings to the connecting rod bearings. Drilled holes in the connecting rods feed oil to the wrist pin bearings. Oil from the wrist pin bearings flows through a drilled hole into the piston “cocktail shaker” cavities to cool the piston crowns. Lube oil from these cavities returns to the crankcase. Refer to Figure 2-28.

On a 900 rpm OP engine, the piston makes its journey from the ODC to the IDC and back 15 times a second. The oil in the connecting rod drilling, the wrist pin area, and the piston crown space develops momentum which causes it to be propelled against the underside of the piston crown. A moment later, this same oil is sent to the other end of the piston as the piston arrives at the ODC position. A drain hole in the piston insert allows this oil to escape and the next time the piston arrives at the IDC position, a fresh charge of lube oil comes up the rod to impact again on the underside of the piston crown. The oil is alternately driven against the piston crown, pulled away and drained, and replenished again on the next stroke.

This is referred to as the “cocktail shaker” action of oil cooling of the piston. The lube oil cooling of the engine is important, but it alone will not keep the piston adequately cooled. In fact, the primary means of keeping the piston from becoming over heated is the next charge of scavenging and combustion air entering the cylinder on the next intake event.

1.1.3 Injection of Fuel into the Cylinder

There are four holes around the center of the cylinder liner. (See Figure 2-32) Two of these holes are for the injection nozzles which spray fuel into the cylinder at the proper time in the cycle. See Figure 2-35. The injection nozzles are connected through high pressure steel tubing to the delivery valve of their injection pump. The injection pump and injection nozzle assemblies will be covered in more detail in a future session. However, while at the model, note the camshafts and how they are driven from the upper crankshaft through a chain drive arrangement. See Figures 2-36 through 2-39.

As the cams rotate, they press down on a plunger in the tappet assembly. The plunger is held against the cam surface by the force of a spring. The cam lobe overcomes the force of the spring and pushes the tappet plunger down as it rotates through the injection cycle for that pump. The tappet plunger in turn, presses down on the injection pump plunger. When the injection plunger is all the way up, fuel fills the space in the injection pump barrel. Then the injection pump plunger moves; it first covers a port and traps the fuel sending it out through the delivery valve to the injection nozzle and into the cylinder. When the injection pump plunger moves a little further, it uncovers the spill port and the injection ends.

The injection pump plunger has a helical cutout that is positioned by means of a gear and rack assembly. By rotating the plunger, the amount of fuel injected is controlled. A system of levers and rods connects the injection pump rack gear to the governor output shaft in such a way that the governor can control the amount of fuel injected as the load or speed on the unit changes. See Figure 2-40.

Two other ports or openings are provided at the center of the cylinder. One is used on OP engines to house the air start check valve, a part of the starting system. The other port is used variously for either a dummy plug, a pressure adapter connection, a cylinder pressure relief cock, or on OP commercial engines, for the gas admission valve. On OP units in nuclear service, the fourth opening is used for a cylinder cock which can be used to relieve cylinder pressure and remove excess oil and/or water when the engine is barred over.

1.1.4 Engine Cooling (See Figure 2-32).

There was a discussion above on the cooling of the piston by the lube oil system. It is also necessary to cool the cylinder liners and this is done with water. A jacket surrounds the cylinder liner to provide a space for the cooling water to pass up along the cylinder. Usually water is supplied by an engine-driven pump. The water enters the engine at one end into the exhaust manifold jacket (on non-turbo engines) or through the exhaust deck bridges (on turbo engines).

At each cylinder, a pair of pipes duct the water into the lower end of the cylinder jacket. The water passes up alongside the cylinder liners as well as going around the four ports at the center of the liner. The water exits the liner at the top on one side. From there a header carries the water from the engine, usually to return it through a temperature control valve to the heat exchanger or radiator.

1.2 ALCO Engine Cut-Away Model Demonstration (See Figure 2-29.)

Many of the features of the ALCO engine are very similar to those of the OP engine just discussed. Emphasis will be made of the primary differences–that of a 4-stroke cycle versus the OP 2-stroke cycle.

The ALCO unit has only one crankshaft and is a ‘V’ configuration engine. It is really two 8-cylinder engines joined at the crankshaft with each bank of the engine tilted away from the other.

The cycle of this engine begins when the pistons are at top dead center (TDC) with both inlet air valves open. As the crankshaft rotates, the piston is moved from the TDC position to the bottom dead center (BDC) position with inlet air valves open. As the piston moves, air is admitted to the cylinders through the intake valves.

Air is supplied to the area around the valves from the intake manifold by suction (non-turbo engines) or by pressure for the turbocharged engines. At the very outward position of the piston or slightly after BDC, the intake valves close and the cylinder is isolated.

From this point on, the air is compressed as the piston approaches TDC. As the air is compressed, its pressure and temperature rise–the air has become heated.

A few degrees before the point that the piston arrives at its (TDC) position, fuel is injected into the cylinder through the injection nozzle in the cylinder head. The injection nozzle sprays fuel under high pressure into the cylinder combustion space beneath the cylinder head. The fuel is first heated by the hot air in the cylinder. When it gets to its ignition temperature of about 450 to 550^{o}F, some of the fuel ignites and begins to burn. This raises the temperature further until soon all of the fuel is burned as it mixes with the oxygen in the air in the cylinder.

By the time the fuel is burning well, the piston has traveled beyond TDC. The pressure in the cylinder is now acting on the piston, which in turn is acting on the connecting rod to create a force that causes the crankshaft to rotate. This is the power stroke of the engine.

In order for the engine to run smoothly, there must be a number of cylinders, timed throughout a revolution of the crankshaft, which fire in sequence. Each cylinder contributes to generating power that is used first, to produce the power necessary for the compression taking place in other cylinders, second, to overcome the friction within the engine, and lastly, to produce power to drive the engine load–in our case, a generator.

As the piston travels toward (BDC), the pressure and temperature in the cylinder is falling due to the increasing volume. When the piston arrives near BDC, the exhaust valves are opened, and the cylinder pressure is further reduced as the exhaust gases escape from the cylinder. In the case of the turbocharged engine, this exhaust pressure drives the turbocharger turbine.

As the crankshaft continues its rotation, the piston travels back to TDC, expelling the exhaust gases. Near TDC, the intake valves open, allowing air to enter the cylinder and scavenge the exhaust gases from the cylinder. There is an overlap between the air intake valve opening and the exhaust valve closing that allows for scavenging and cooling. Since the valves are usually both on the same end of the cylinder, there is no ‘uniflow’, but a loop or cross flow performs the scavenging process. At this point, the crankshaft has made two complete revolutions, and the piston has made four strokes.

For further information on the 4-stroke cycle engine, see Figures 2-7 through 2-13.