4.0 FUEL, AIR, AND ENGINE GOVERNING

This chapter presents the basis and principles of diesel fuel, combustion air, and engine governing systems and shows their inter-relationship.

Learning Objectives:

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

1. Describe the relationship between the intake air charge and fuel delivery in the development of power in a diesel engine.
2. Identify the major components of the diesel engine air intake and exhaust systems and state the purpose of each.
3. Identify the major components of a diesel engine fuel system and state the purpose of each.
4. List the functions that must be performed by the components of a diesel engine fuel injection system.
5. Describe the construction and explain the operation of a typical diesel engine fuel injection pump.
6. Describe the construction and explain the operation of a typical diesel engine fuel injection nozzle.
7. Describe the construction and explain the operation of a unit type diesel engine fuel injector.
8. Describe how the diesel engine governor operates to control the fuel delivery to each cylinder.
9. Describe the exhaust system functions, construction, and operation.

NOTE: Text, illustrations, and examples in this chapter are based on a typical nuclear application and therefore may not apply to a specific application.

4.1 Introduction to the Air and Fuel Systems

In Chapter 2, we discussed the three elements of combustion: fuel, oxygen, and heat. The power developed by the diesel engine is directly related to the amount of fuel it can burn efficiently. In this chapter, we discuss the inter-relationship of these elements in the development of power and the manufacturer's rating of a diesel engine.

4.1.1 Air and Fuel for Combustion

4.1.1.1 Composition of Air

Air is composed primarily of nitrogen and oxygen. By weight, 76% of the air is nitrogen (N_2) while 23% is oxygen (0_2). The remaining 1% is made up of other substances such as carbon dioxide, carbon monoxide, water vapor, dust, and other such materials and gases. Of this mixture, only the oxygen is required for combustion.

4.1.1.2 Composition of Fuel

Fuel oil is comprised mostly of the two elements, hydrogen and carbon; hence, its classification as a "hydrocarbon" fuel. By weight, this composition is approximately 15 % hydrogen (H_2) and 85 % carbon (C). Fuel oil also contains small amounts of sulfur and other such substances. Paraffin based fuel oil has the empirical chemical formula C_nH_{2n+2}

Fuel oil specifications are normally established by the engine manufacturer and incorporated into plant Technical Specifications (TS). Generic fuel oil specifications include the following:

- Cetane Number: 40 (Minimum)
- Total Sulfur: 0.05% (Maximum)
- Organic Chlorides: 20ppm (Total, Max)
- Viscosity: 2-40SUS @ 100ºF
- Ash Content: 0.02% (by Weight)
- Heating Value: 18,190 BTU/lb Minimum
- Cloud Point: above 40^{o}F

NOTE: Maximum Sulfur content of Diesel Fuels have recently been revised to 0.05% (from 0.5%). The effect of Low Sulfur or Ultra-low Sulfur content in the fuel is not known at this point. Since EDG's run very seldom compared to commercial/municipal units, the effect of low sulfur will probably not be significant on these units.

4.1.2 The Combustion Process

4.1.2.1 Combustion with Theoretical Air

Let us assume we mix a specific amount of fuel with exactly the amount of air (theoretical air) required for combustion. This is based on the diesel engine operating at full load. In such a mixture, each carbon (C) atom and each hydrogen (H) atom will be in contact with the required number of oxygen (O) atoms for complete combustion. Theoretically then, the maximum conversion of chemical energy to thermal energy would occur. Under these conditions, the following stoichiometric (chemically correct) reaction will occur.

$$2C_nH_{2n+2} + (3_n + 1)O_2$$

$$\rightarrow 2nCO_2 + (2n + 2)H_20$$

Actually, not every atom of fuel mixes with exactly the correct number of oxygen atoms. This is the result of such conditions as incomplete mixing, residual exhaust gases in the cylinder, and the presence of various contaminants in the air. Under these conditions, complete combustion cannot occur.

4.1.2.2 Combustion with Excess Air

In order to compensate for these less than perfect conditions and to ensure that nearly complete combustion does occur, diesel engines are designed to operate with 15 to 25 % excess air.

4.1.2.3 Air to Power Relationship

Assuming all other factors are equal, the relationship of air flow to the power which can be developed by a diesel engine is as follows:

- The greater the mass of air entering the engine, the more oxygen will be available to support combustion.
- The more oxygen available to support combustion, the more fuel can be injected into the cylinder which will burn efficiently.

- The more fuel which can be burned efficiently, the more usable power the engine can develop.

4.1.3 The Combustion Process

We will begin this section by examining the series of events which occur in the cylinder as the fuel oil is sprayed into the heated air charge. This fuel charge goes through the four phases listed below as combustion occurs. Refer to Figure 4-1 and points C, D, and E on Figure 4-2 for the following discussion.

4.1.3.1 Delay Period

A delay period occurs from the timing of the initial injection to when the actual ignition takes place. The delay period consists of two parts. First, the physical delay, which is the time it takes the fuel to atomize, mix with the air charge, and vaporize. This creates a mixture of air and fuel. Second, the chemical delay is the localized pre-flame oxidation caused by the catalytic effect of wall surfaces, high temperatures, and miscellaneous particles. These localized regions can reach temperatures of from 1000 to 2000°F.

4.1.3.2 Rapid Combustion

After the delay period, there is rapid combustion of the fuel which entered the cylinder during the delay period.

4.1.3.3 Continued Combustion

As fuel continues to be injected, normal combustion occurs increasing the temperature and pressure of the heated gases within the cylinder. Normal peak temperatures for such combustion range from 3500 to 4500°F.

4.1.3.4 After-burning

After the injection is completed, there is an after-burning period where any remaining fuel combines with the remaining oxygen to complete the burning process.

4.2 The Intake Air System

4.2.1 Intake Air System Requirements

In order for the engine to operate efficiently and reliably, the intake air system must provide the following:

4.2.1.1 Sufficient Quantity

The system must supply a sufficient quantity of air to each cylinder to support complete combustion under maximum load. This quantity must include the 15 to 25 % excess air for combustion.

For 2-stroke cycle engines, additional air must also be provided to ensure proper scavenging of the spent gases from the cylinders.

4.2.1.2 Clean Air

The incoming air charge must be clean. That is, it must be free of abrasive particles which would damage the engine's internal components. The incoming air must also be free of gaseous contaminants which do not participate in the combustion process.

4.2.1.3 Cool Air

The mass of air which can be contained in a specific volume is dependent on the density of that air. As the temperature of air increases, its density decreases, provided its pressure remains constant. Air that is too warm will not provide sufficient oxygen to support complete combustion.

4.2.1.4 Reduced Noise Levels

Due to the cyclical action of the engine, pressure pulsations tend to develop in the flow of the incoming air charge. These pressure pulsations cause an increased noise level within the diesel space. They also create vibrations in the intake air piping, which can lead to damage and component or system failure. Flexible connections are usually provided to permit thermal expansion and isolate engine vibrations from the piping.

4.2.2 The typical Intake Air System

The intake air system shown in Figure 4-3 (the right hand section) displays the components which would be found in a typical nuclear plant application.

4.2.2.1 Intake Air Filter

Sometimes referred to as an air cleaner, the intake air filter removes particulate suspended in the air prior to entering the system. It also helps to remove any excess moisture in the air and in many instances, reduces the noise level of the incoming air charge.

Various types of air filters are used. Sometimes, two types will be combined for a single application. The two most common types, dry and oil bath, are discussed in detail below.

- **Dry Type Filters** (Figure 4-4) use a porous, fibrous cloth or paper type media. As the air passes through the media, the media captures and holds the airborne particulate allowing only clean air to reach the engine. Periodically the media becomes restricted due to a buildup of the particulate. Since this restriction then reduces the air flow to the engine, the media or elements must be replaced.

- **Oil Bath Air Cleaners** are very effective at removing particulate from the incoming air the charge. The oil bath air cleaner shown in Figure 4-5 consists of a cylindrical housing, internal air piping, an oil reservoir, a wire mesh filter, and various baffles.

The incoming air enters the housing and travels downward toward the oil reservoir. As the air reaches the surface of the oil reservoir, it is forced to change direction 180^{o}. This sharp change in direction causes the heavier particles to separate from the air and become trapped by the oil. The air and lighter particles pick up some of the oil and carry it upward into the wire mesh. The oil and lighter particulate become trapped by the wire mesh allowing only clean air to pass on to the engine.

Over time, the oil and particulate fall back into the oil reservoir. Periodic cleaning of the oil reservoir and wire mesh is all that is required to prepare the unit for continued operation.

4.2.2.2 Intake Air Silencer

The intake air silencer consists of a plenum type housing which may include chambers and baffles to reduce or dampen the pulsations which have developed in the incoming air flow. Often, some form of sound deadening material may be included. In some installations, the intake air silencer is incorporated into the intake air filter.

4.2.2.3 Intake Air Piping

The intake air piping makes the physical connection between the intake air filter and silencer. This piping should be as short as possible and as large in diameter as practical so as to provide a minimal resistance to the air flow. Sharp bends and fittings should be kept to a minimum to ensure free air flow to the engine.

4.2.3 Blowers and Turbochargers

As discussed previously, the power an engine can develop depends on the amount of air available for combustion. By mechanically increasing the air flow into the engine, we can substantially increase the power produced by that engine. Two devices are commonly used on diesel engines to increase the quantity of intake air reaching the cylinders.

4.2.3.1 Blower/Supercharger

The blower (Figure 4-6), commonly referred to as a supercharger, is a positive displacement air pump which delivers a positive flow of air to the engine. It consists of a pair of helical rotors inside a special housing. As the rotors rotate, they draw air in through the intake air piping, force it through the blower housing and discharge the air into the intake air manifold or air box.

These devices are mechanically driven by the engine accessory drive gear train. As such, the quantity of air delivered by the blower is a function of the engine rpm. These units require substantial amounts of horsepower to operate; however, the power gained from the increased air flow more than offsets the power needed to operate the device.

4.2.3.2 Turbocharger (Figure 4-7)

The turbocharger also provides an increase in intake air flow to the engine with a corresponding increase in power output. Unlike the blower, the turbocharger uses a centrifugal compressor. The impeller is surrounded by a scroll-shaped compressor housing, much like a centrifugal pump. The impeller is attached to the turbine shaft. A turbine wheel is attached to the other end of the turbine shaft. This turbine wheel is encased in a turbine housing which is connected to the compressor housing by the bearing housing. The inlet of the turbine housing is connected to the outlet of the engine exhaust manifold.

Hot exhaust gases, which contain a substantial amount of thermal energy, enter the turbine housing, pass through a set of stationary blades, and are directed against the blades of the turbine wheel. As these gases pass through the turbine wheel, they expand and cool, thereby releasing energy to rotate the turbine wheel. This action in turn causes the compressor wheel to rotate.

Air is drawn into the center (inducer) of the compressor wheel. Rotation of the compressor wheel throws the air radially, by centrifugal force, increasing its velocity (kinetic energy). As the air exits the compressor wheel at high velocity, it enters the plenum like compressor housing. The velocity of the air is suddenly decreased resulting in a sharp increase in the pressure in the compressor housing. This increase in pressure is what boosts the air flow entering the engine cylinders.

4.2.3.3 Blower vs Turbocharger

There are significant advantages in using a turbocharger rather than or in addition to a mechanically driven blower.

1. Since the turbocharger is powered by the heat of the exhaust gases, it does not require any power directly from the engine. It does present a restriction to the exhaust gas flow and therefore creates a back-pressure in the exhaust manifold. However, the overall result is a greater increase in engine power output than would be attained with an engine driven blower.

2. The increased mass of intake air provided by the turbocharger is determined by the heat energy of the exhaust gases leaving the engine. The temperature and mass flow of the exhaust gases are functions of the quantity of fuel being burned in the cylinders, which is in turn a function of the load applied to the engine. As the load on the engine increases, the quantity of fuel burned increases. This increase in heat input to the engine increases the heat energy of the exhaust and therefore the amount of energy driving the turbocharger. The result is an increase in the mass of air entering the cylinders and a subsequent increase in engine power which gives the turbocharger a unique load-following ability not available with a blower.

Some engines, such as the Fairbanks-Morse opposed piston engine, efficiently combine a turbocharger and a blower. See Figure 4-8.

4.2.3.4 Intercoolers - Aftercoolers

Turbochargers, while increasing the flow of intake air to the cylinders, also increase the temperature of the air. This increase in air temperature reduces the density of the air charge and therefore the amount of oxygen available for combustion.

To compensate for this reduction in density, most turbocharged diesel engines utilize heat exchanger devices known as intercoolers or aftercoolers. These are air-to-jacket-water heat exchangers located between the discharge of the turbocharger and the air intake manifold or air box. They reduce the temperature of the intake air charge by transferring the excess heat from the air charge to the engine jacket water cooling system.

The water for cooling the Intercooler-aftercooler will be discussed further in Chapter 6, “Engine Cooling Systems.”

4.2.3.5 Diesel Engine Ratings

The quantity, quality, and temperature of ambient and combustion air directly affect engine performance. Therefore, engine manufacturers rate and de-rate their engine based upon a set of standard (stated) conditions. A typical basis for ratings for one manufacturer is illustrated by Figure 4-9.

4.3 The Exhaust System

Just as the intake air system is designed to efficiently supply fresh air to the cylinders, the exhaust system is designed to efficiently remove burned or spent gases out of the cylinders. To maximize the amount of air available for combustion, the exhaust system must minimize the amount of spent gases remaining in the cylinders. The basic configuration of a diesel engine exhaust system is shown in Figure 4-3 (the left half).

4.3.1 Exhaust System Requirements

Following are the fundamental requirements of the engine exhaust system:

4.3.1.1 Minimal Resistance to Flow

The exhaust system must be designed and constructed in such a manner that it is a minimum resistance to gas flow. Engine horsepower ratings are based upon not exceeding a specified exhaust back pressure.

4.3.1.2 Reduce Noise Levels

The high energy level and large volume of exhaust gas flow can create a substantial noise problem. The exhaust system must include some form of noise suppression device to reduce the noise level of the exhaust gases to an acceptable level.

4.3.1.3 Direct Exhaust Gas Flow

The system must be designed and constructed in a manner which will direct the exhaust gases far enough away from the combustion air intake to prevent the cross-over of exhaust gases into the air intake, thereby contaminating the intake air and reducing the effectiveness of the combustion process.

4.3.2 Exhaust System Components

4.3.2.1 Exhaust Manifold or Header

The exhaust manifold or header collects the exhaust gases at the cylinder heads or exhaust ports and directs the gas flow to the inlet of the turbocharger. Some exhaust manifolds or headers are water cooled which reduces the buildup of heat in the diesel engine space.

4.3.2.2 Exhaust Gas Silencer

Known more commonly as a muffler (Figure 4-10), the exhaust gas silencer reduces exhaust noise by dampening the pulsations resulting from the cyclical action of the engine. This is accomplished by passing the gases through a series of chambers and baffles causing a gradual expansion of the gases and a reduction in noise emission.

4.3.2.3 Exhaust Safety Valve

In nuclear applications where the exhaust gas silencer and/or piping are exposed to the atmosphere and unprotected, an automatic safety valve may be installed. This device, which functions similarly to a conventional safety valve, is either spring loaded or weight loaded in the closed position. Some are simply a thin sheet of metal (such as aluminum foil) which will rupture at an excessive pressure. Should the exhaust system downstream of the valve become damaged or clogged, the back-pressure in the exhaust will increase. When the back pressure in the exhaust system exceeds a specified value, the valve will automatically open, or rupture, discharging the gases to the atmosphere and allowing the engine to continue to operate.

4.4 The Diesel Engine Fuel System

Once the cylinder has been charged with air and the air compressed, raising its temperature above the ignition point for the fuel oil, a metered quantity of fuel is sprayed into the cylinder and combustion occurs.

4.4.1 Fuel System Functions

The diesel engine fuel system can be divided into three separate but interdependent subsystems. Each system must perform reliably and efficiently in order to support the operation of the engine.

4.4.1.1 Fuel Oil Storage and Transfer System

The first of these systems, the fuel oil storage and transfer system, stores a sufficient quantity of fuel oil to supply the engine for a specified period of time while operating at full power. This period of time must be sufficient to allow for the delivery of replacement fuel from the designated supplier.

Fuel is automatically transferred from the storage tank to the fuel oil day tank to maintain a positive head on the suction of the engine-driven and electrically driven fuel oil supply pumps.

4.4.1.2 Fuel Oil Supply System

This system maintains a limited supply of fuel in the fuel oil day tank, which is located near the engine, to provide a positive pressure head at the inlet of the fuel oil supply pump. The supply pump takes its suction from the fuel oil day tank and supplies the fuel oil to the fuel injection system components at a relatively low pressure (e.g. 45 psig).

4.4.1.3 Fuel Injection System

The fuel injection system has the most precise and demanding job of the three systems. Regardless of the type of system used, the fuel injection system must perform each of the following functions:

- Meter the quantity of fuel delivered to each cylinder to control the power produced by the engine.
- Inject the fuel into the heated air charge at a time relative to the rotation of the crankshaft, which produces the desired combustion characteristics.
- Inject the fuel at a rate which will ensure smooth, complete, efficient combustion.
- The injection must begin and end quickly. This is to prevent uncontrolled distribution and poorly atomized fuel from entering the cylinder. Under these conditions, the fuel would not mix adequately with the oxygen in the

cylinder which would waste fuel and produce soot and other undesirable combustion by-products.

- The fuel must be sufficiently atomized to provide optimum mixing of the fuel with the compressed air charge. The more effective the atomization, the more complete the combustion.

- The fuel spray must be distributed evenly throughout the combustion space. This too helps to ensure effective mixing and therefore complete combustion.

4.4.2 Fuel Oil Storage and Transfer System (Figure 4-11)

4.4.2.1 Fuel Oil Storage Tank

Typically the fuel oil storage tank is underground and sized to provide the engine with a specified (e.g. 5- or 7-day) fuel supply when operating at full power. The required size of the tank depends on the rate of fuel consumption for the engine and the heat value for the grade of fuel oil being used.

The fuel oil storage tank usually incorporates a low point or sump for the collection and removal of water and sediment. This low point can be pumped out periodically to remove the moisture and other contaminants.

In determining actual available accessible fuel, consideration must be given to the amount of fuel available between the pump suction level and the lowest level before tank refill.

4.4.2.2 Fuel Oil Transfer Pumps

The fuel oil transfer pumps are normally single stage centrifugal pumps which draw a suction on the fuel oil storage tank to transfer fuel oil into the fuel oil day tank. They are controlled by level switches in the day tank to ensure a minimum fuel oil level is maintained.

The fuel oil transfer pumps may be placed in one of three locations depending on the site specific design.

- The pumps may be submerged below the fuel oil level in the fuel oil storage tank. While ensuring a positive suction head for the pumps, this configuration makes pump maintenance somewhat difficult.

- A second option involves locating the pumps in a pit placing the suction connection below the fuel level in the storage tank. Pump access is improved but still less than ideal.

- A unique approach involves placing the pumps in the diesel room at floor level while placing jet pumps (ejectors) inside the fuel oil storage tank (as shown in Figure 4-11). These pumps do not draw suction directly from the storage tank but from the fuel oil day tank and discharge to the nozzle of the jet pumps. The venturi action of the jet pumps transfers the fuel oil into the fuel oil day tank. This method allows for easy maintenance of the transfer pumps and the jet pumps since they have no moving parts and require no maintenance.

4.4.3 Fuel Oil Supply System (Figure 4-12)

4.4.3.1 Fuel Oil Day Tank

This tank stores a limited amount of fuel at a location near the diesel engine. It may be located in the diesel room itself or in a room adjacent to the diesel room. The size of the tank depends on its location and on any governing codes or standards, including applicable technical specifications.

The tank is usually positioned so the fuel level is even with or above the suction of the fuel oil supply pumps to ensure a positive flow into the pumps. Automatic level switches in the day tank activate the fuel oil transfer pumps to ensure the level of the fuel in the tank is kept above a specified minimum.

4.4.3.2 Fuel Oil Strainers (Figure 4-13)

These strainers, located between the fuel oil day tank and the suction of the fuel oil supply pumps, remove large particulate, sediment, and moisture from the fuel.

They are usually of the duplex type incorporating a three-way valve which allows one strainer element to be taken out of service for cleaning while the unit remains operational. The strainer element is usually a fine wire mesh which can be removed periodically for cleaning.

It is recommended on duplex type units that the valving be left in a position that uses only one of the strainer elements; the other then being immediately available when needed (rather than both units being plugged in case of a problem).

4.4.3.3 Fuel Oil Supply Pumps (Figure 4-14)

Two fuel oil supply pumps are normally provided. One is engine driven and is operational whenever the unit is operating. An electric-driven supply pump is also provided to ensure positive fuel flow during startup before the engine-driven pump can provide sufficient pressure for engine operation.

These pumps are usually positive displacement gear type pumps though some applications use screw type pumps. They supply fuel oil to the fuel injections system under a fairly low pressure (e.g. 45 psig).

4.4.3.4 Fuel Oil Filters (Figure 4-15)

These filters, located between the discharge of the fuel oil supply pumps and the fuel oil manifold or header, remove any minute particles (e.g. 5 micron as specified by the engine manufacturer) which may be in the fuel.

These units are normally of the duplex type with a three-way valve to allow for replacement of the elements while the engine remains in operation. The elements use a paper or fabric like media to trap these extremely small particles. Again, it is best to leave the valve handle in a position to use only one of the filter elements.

4.5 <u>Fuel Injection Systems</u>

Two basic types of fuel injection systems are commonly used on diesel engines. The pump and nozzle system is a two-part system incorporating an injection pump and a separate nozzle. The unit injector system combines the injection pump and nozzle into a single unit.

4.5.1 Fuel Injection Pump and Nozzle System (Figure 4-16)

In the pump and nozzle system, a fuel injection pump, operated by the engine camshaft, meters the fuel, injects the fuel at the proper time and proper rate, and starts and stops the delivery quickly to ensure clean, efficient combustion. The injection nozzle, mounted in each cylinder head (on 4-stroke and 2-stroke conventional engines) or through the wall of the cylinder liner (on opposed piston engines), atomizes the fuel while distributing it evenly throughout the combustion space.

4.5.1.1 Injection Pump Construction (Figure 4-17)

The main components of the injection pump are the plunger and barrel. These two items are precision machined and carefully fitted together to ensure precise delivery of the fuel. Together, the plunger and barrel regulate the quantity of fuel entering the cylinder while establishing other injection characteristics such as injection timing and injection rate.

The pump body (1) is the main structural and pressure-retaining component of the pump. It houses the plunger and barrel assembly (12).

A spur gear (9), which is keyed to the plunger, allows the plunger to be rotated for the purpose of fuel metering. A fuel control rack (2) engages with the spur gear which provides a means for rotating the plunger from outside the body.

The return spring (11) and spring retainer (13) return the plunger to the non-delivery position while keeping the cam follower in contact with the injection cam.

A delivery valve assembly (20) at the discharge of the plunger acts as a spring-loaded check valve which prevents the back flow of fuel during non-delivery.

4.5.1.2 Injection Pump Operation

The following information refers to the injection pump shown in Figure 4-17. Though there are different designs of injection pumps, all operate on the principle of the near incompressibility of liquids.

- **Principle of Operation** - The plunger is precision-fitted to the barrel which has both a fill and spill port. A single or double helix is cut into the end of the plunger. A slot or drilled passage connects the delivery end of the plunger to the helix.

  The plunger has a mechanically constant stroke length established by the lift of the injection cam lobe. The fuel delivery is determined by the "effective" stroke length which is created by the indexing of the fill and spill ports with the plunger helix. The effective stroke is that portion of the mechanical stroke where both the fill and spill ports are simultaneously blocked. Whenever both ports are closed at the same time, fuel pressure builds up within the barrel and is then directed to the nozzle assembly. Rotation of the plunger within the barrel changes the relationship of the helix to the ports. This changes the length of the effective stroke and, therefore, the quantity of fuel delivered to the cylinder.

- **Zero Fuel Delivery** (Figure 4-18)- At zero delivery, the slot aligns with one of the ports so that there is no time when both ports are covered simultaneously. Fuel moves back and forth through the slot and in and out of the spill port.

- **Engine Idling** - With the plunger at the bottom of its stroke, fuel enters through the fill port to fill the barrel. As the plunger moves upward, both ports become blocked and fuel is delivered to the injection nozzle and injected into the cylinder.

  Continued upward movement of the plunger delivers fuel until the helix uncovers the spill port at which time the injection ceases, and fuel passes through the slot and out the spill port.

  The plunger completes its strokes, returning to the bottom of its stroke where it is again filled with fuel.

- **Low Power** - At low power, the plunger is rotated as shown in Figure 4-19. With the plunger at the bottom of its stroke, the barrel again fills with fuel. Upward movement of the plunger closes off both ports. Fuel continues to be delivered until the helix uncovers the spill port stopping the fuel injection. Rotation of the plunger has increased the effective length of the stroke and therefore the amount of fuel injected into the cylinder.

- **Full Power** - At full load, maximum fuel delivery is required. The plunger is now rotated as shown in Figure 4-20. With the plunger at the bottom of its stroke, the barrel is again filled with fuel.

  Upward movement of the plunger blocks off both ports and begins the delivery of fuel into the combustion chamber. With the plunger in the full fuel position, the ports are covered for the greatest amount of time with the maximum amount of fuel entering the cylinder.

  As the helix uncovers the spill port, fuel delivery stops just as before. The plunger then completes its stroke and returns to bottom position to be refilled.

4.5.2 Fuel Injection Nozzles (Figure 4-21)

The fuel injection nozzle has the job of atomizing the fuel as it enters the combustion space and distributing the fuel evenly for efficient combustion.

4.5.2.1 Nozzle Body or Housing

The housing or body is the main structural and pressure retaining component of the assembly. Fuel supply and return lines connect to the upper end of the nozzle body while at the lower end is the nozzle spray tip.

4.5.2.2 Nozzle Spray Tip (Figure 4-22)

The spray tip actually enters the combustion space. A series of small holes in the tip atomize the fuel as it passes through. The size of the holes determines the degree of atomization while the number of holes and their angle distribute the fuel evenly and correctly throughout the combustion chamber.

4.5.2.3 Pintle Nozzle (Figure 4-23)

Some engines, such as the Fairbanks-Morse opposed piston, use a single hole "pintle" type nozzle. Here, a small plunger or pintle passes through the single hole. As the fuel is delivered, the pintle lifts up creating a cone- shaped fuel spray which atomizes and distributes the fuel for efficient combustion.

4.5.2.4 Nozzle Valve Assembly

The nozzle valve assembly consists of a needle valve in a fitted and lapped cylinder. The nozzle valve assembly may be part of the spray tip or a separate unit. Its primary job is to prevent combustion gases from entering the nozzle assembly. The nozzle valve is held in the seated position by the nozzle spring assembly.

4.5.2.5 Nozzle Spring Assembly

A spring seat directs the force of the spring against the upper tip of the nozzle valve. The force of the spring acting on the nozzle valve sets the pressure of the fuel being injected into the cylinder. The spring force is adjustable by either adjusting a screw or changing the thickness of the shim pack at the upper end of the spring.

4.5.3 Injection Nozzle Operation (Fig. 4-21)

The fuel delivered by the injection pump passes through a heavy walled fuel pipe to the nozzle assembly. This fuel is directed through internal passages in the nozzle body to the nozzle valve near its seat.

The high pressure fuel creates an upward force against the needle valve. When the force of the fuel is sufficient to overcome the spring force, the nozzle valve unseats, and fuel is injected into the combustion space. As soon as fuel delivery stops, the sudden drop in pressure allows the nozzle valve to quickly seat, stopping the injection.

4.5.4 Unit Type Fuel Injectors

The unit type injectors, such as those used on the EMD 2-stroke cycle engine, combine the injection pump and injection nozzle into a single "unit" installed in each cylinder head. With this type injector, the high pressure fuel lines are eliminated along with their potential for leakage.

The main components of the unit type injector are the matched and lapped plunger and bushing assembly as shown in Figure 4-24. This plunger uses an upper and lower helix to control injection timing and duration with a T-shaped drilled passage to bypass the fuel. The bushing has an upper port and a lower port positioned 180^{o} to each other.

The body and nut form the structural portion of the injector. The rack gear engages with the spur gear which is indexed to the plunger. The spur gear causes the plunger to rotate while allowing it to move freely up and down.

A follower, actuated by the injector lobe on the engine cam lift, connects to the end of the plunger. The follower spring returns the plunger to its upper most position when the cam in on its base circle.

A check valve located below the plunger and bushing prevents the back flow of fuel during the upward stroke of the plunger.

A spring-loaded needle valve is located in the injector spray tip. The spring holds the valve seated while establishing the injection pressure.

4.5.5 Injector Operation (Figure 4-25)

The fuel pump supplies fuel to the unit injector at approximately 50 psi. This eliminates the need for the high pressure fuel piping of the pump and nozzle system.

As with the injection pump discussed previously, fuel injection occurs whenever both ports (upper and lower for unit injectors) are closed simultaneously.

Figure 4-25 illustrates the following. With the plunger at the top of its stroke, fuel enters through the lower port to fill the cavity below the plunger. The fuel also travels upward through a drilled passage in the plunger and bypasses out the upper port.

Downward movement of the plunger closes the lower port but allows fuel to bypass out the upper port. Injection begins as soon as the upper port is closed by the helix on the plunger. Fuel is delivered as long as both ports are closed.

Injection stops when the lower helix uncovers the lower port and fuel begins to bypass the plunger and out the lower port into the fuel return passages of the injector body. The plunger continues downward to the end of its mechanical stroke.

4.5.5.1 Zero Fuel Delivery (Figure 4-26)

With the plunger in its upper most position, fuel passes through the lower port to fill the bushing. As the plunger moves downward, the plunger blocks off the lower port, and fuel bypasses through the drilled passage.

When the engine is to be shut down, the fuel control racks are moved to the zero fuel position. This indexes the helix of the plunger to the ports as shown in Figure 4-26. In this position, there is no time during the stroke when both ports are blocked simultaneously. Fuel simply bypasses into the return passages in the body of the injector, and none is delivered to the cylinder.

4.5.5.2 Low Power (Figure 4-27)

At idle or low power, the bushing is filled while the plunger is at its upper most point of travel. Downward movement of the plunger blocks off the lower port, and the fuel bypasses the plunger and exits through the upper port until the upper helix closes the upper port. Injection begins as soon as the upper port is covered and continues until the lower helix passes the lower port allowing the fuel to bypass into the return passages of the injector body.

The beginning of the injection is determined by the upper helix while the ending of the injection is regulated by the lower helix. As in the other injectors, the effective stroke is the distance the plunger travels when both ports are blocked.

4.5.5.3 Full Fuel (Figure 4-28)

For maximum fuel delivery, the plunger is indexed as shown in Figure 4-28. With the bushing full, injection begins as the upper helix blocks the upper port. Downward movement of the plunger delivers fuel until the lower helix uncovers the lower port.

In this orientation, the effective stroke length is at its maximum. Maximum fuel is delivered leading to maximum power output for the engine.

4.5.5.4 Needle Valve Action (Figure 4-24)

The high pressure fuel is directed through internal passages to the needle valve. The force of fuel acting on the needle valve causes the valve to overcome the spring force and inject fuel into the combustion space.

4.5.5.5 Injector Timing

Static injector timing is established by the relationship between the injector plunger and the fuel injection lobe on the engine camshaft. During engine operation, timing must change slightly according to the load on the engine. This incremental timing is accomplished by the shape of the helix on the plunger. As the engine load increases, the helix closes off the upper port earlier in the timing sequence which gives the cylinder more time to complete the combustion process.

4.6 Introduction to Governors

The power developed by the engine is dependent on the quantity of fuel burned in the cylinder for each power stroke. Since there is no throttling device for the intake air, a diesel engine without some controlling mechanism could run to the point of self-destruction. In order to provide the necessary control, all diesel engines are equipped with some form of engine governor.

4.6.1 Governor Functions

Governors control the engine speed or power by regulating the amount of fuel delivered to the cylinders for each power stroke of the piston. They function by measuring various engine parameters and change the fuel delivery to meet the engine demand. Actual fuel control is accomplished by mechanically connecting the governor terminal shaft lever to the injection pump fuel control racks (rack gears). In this way, governor action causes rotation of the plunger or barrel which regulates fuel delivery to control engine power.

When operating your automobile, you act as the governor. Assume you are cruising an interstate on level ground at 55 MPH, and you encounter a hill. As you start to climb the hill, your speed begins to drop off. In order to maintain the desired 55 MPH, you push down on your accelerator to give the engine "more gas," and therefore, more power. You will then reach a point where the fuel delivery and power just balance the load demand on the engine, and you again maintain your desired speed.

As you crest the hill, the car begins to speed up. You automatically back off on the accelerator pedal to reduce the fuel delivery and reduce the power. Again, a balance is achieved, and you return to the desired 55 MPH.

Diesel generators, regardless of their application, require a governing device which is more reliable, more sensitive, and faster acting than would be possible with human control.

The primary purpose of discussing the governor in this section is to make the connection between the governor or governing system and the fuel injection equipment. The fuel injection system controls the fuel that is injected into the cylinders of the engine to generate power. The purpose of the governor is to control the fuel injection system so as to maintain the speed or frequency of the units output.

4.6.2 Nuclear Application Governors

Diesel engines used to supply Class 1E power to electrical load at nuclear power plants require very precise control to ensure proper operation under emergency conditions. Governors specific to nuclear applications will be covered in detail in Chapter 8. Engine controls are discussed in Chapter10.

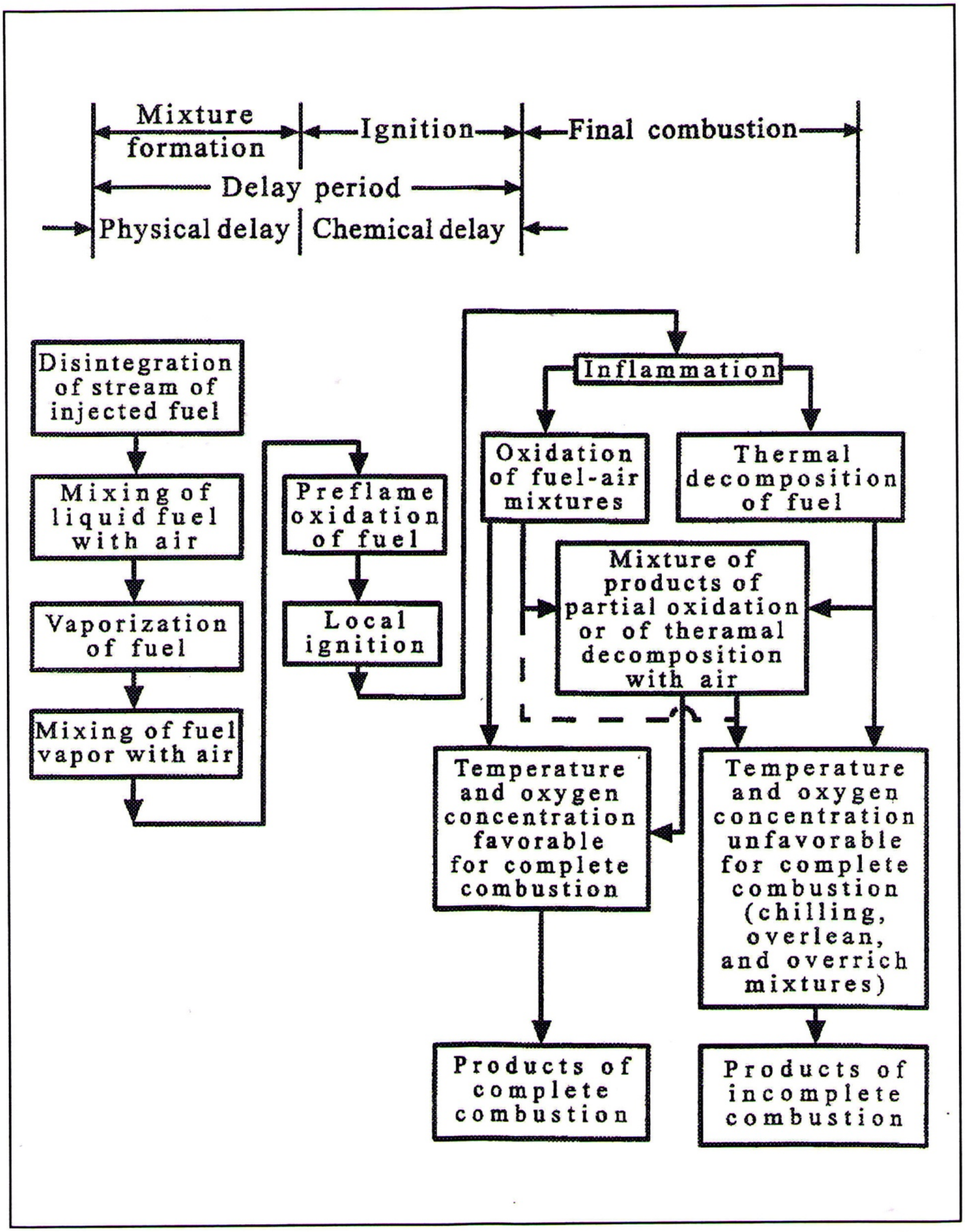


Figure 4-1 Combustion Activity

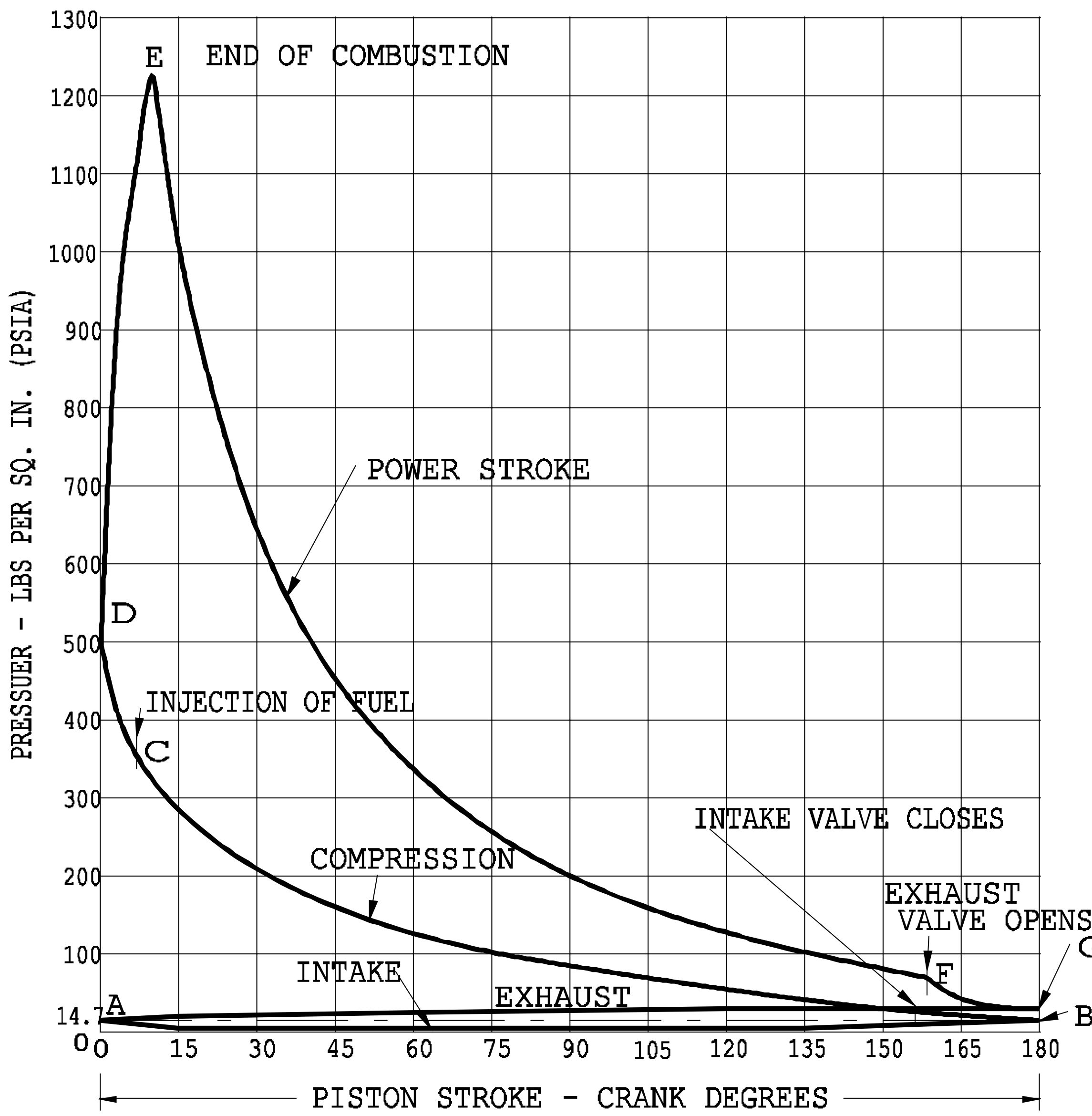


Figure 4-2 Diesel Cycle – Pressure vs Stroke

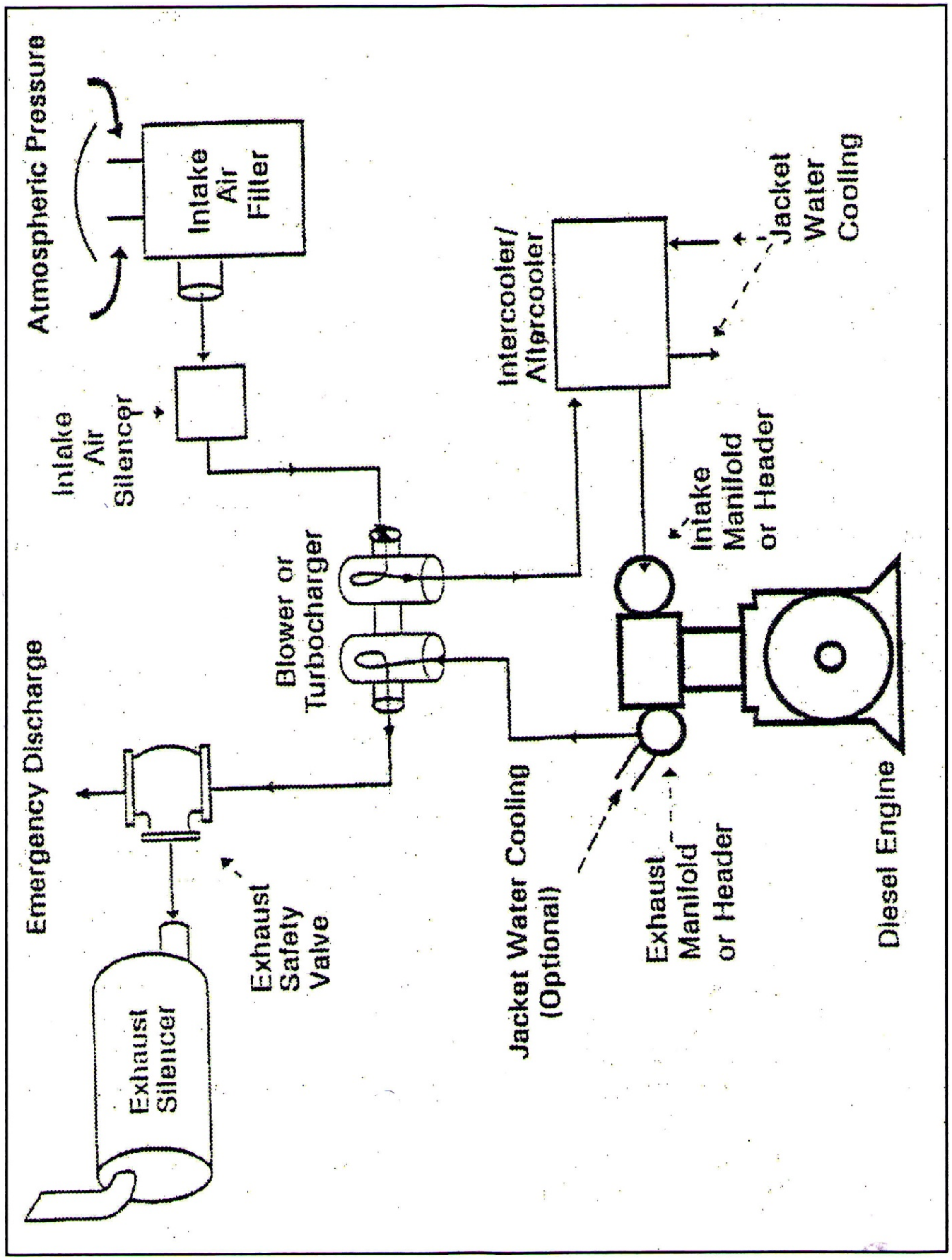


Figure 4-3 Basic Intake and Exhaust System

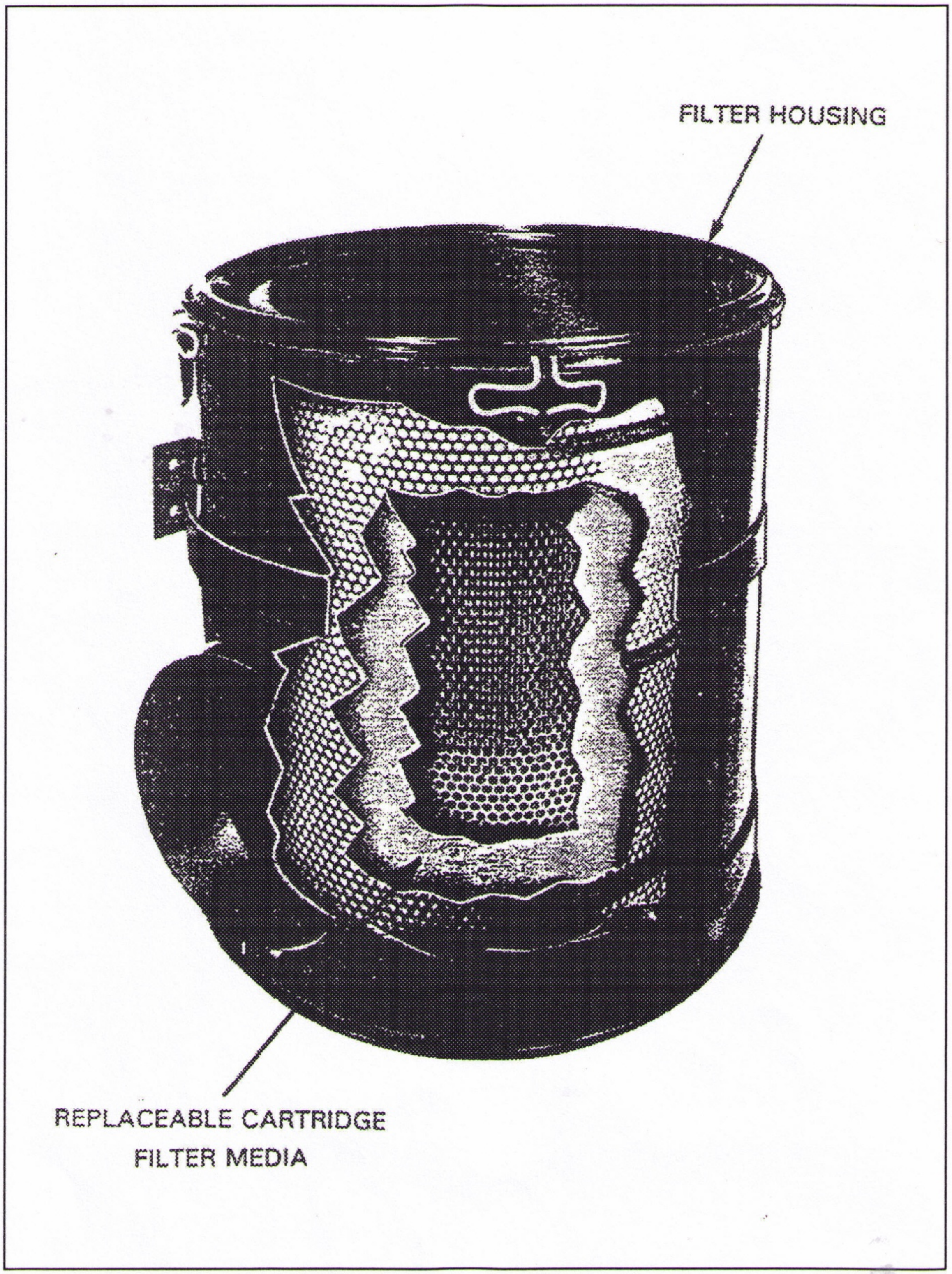


Figure 4-4 Dry Type Air Filter

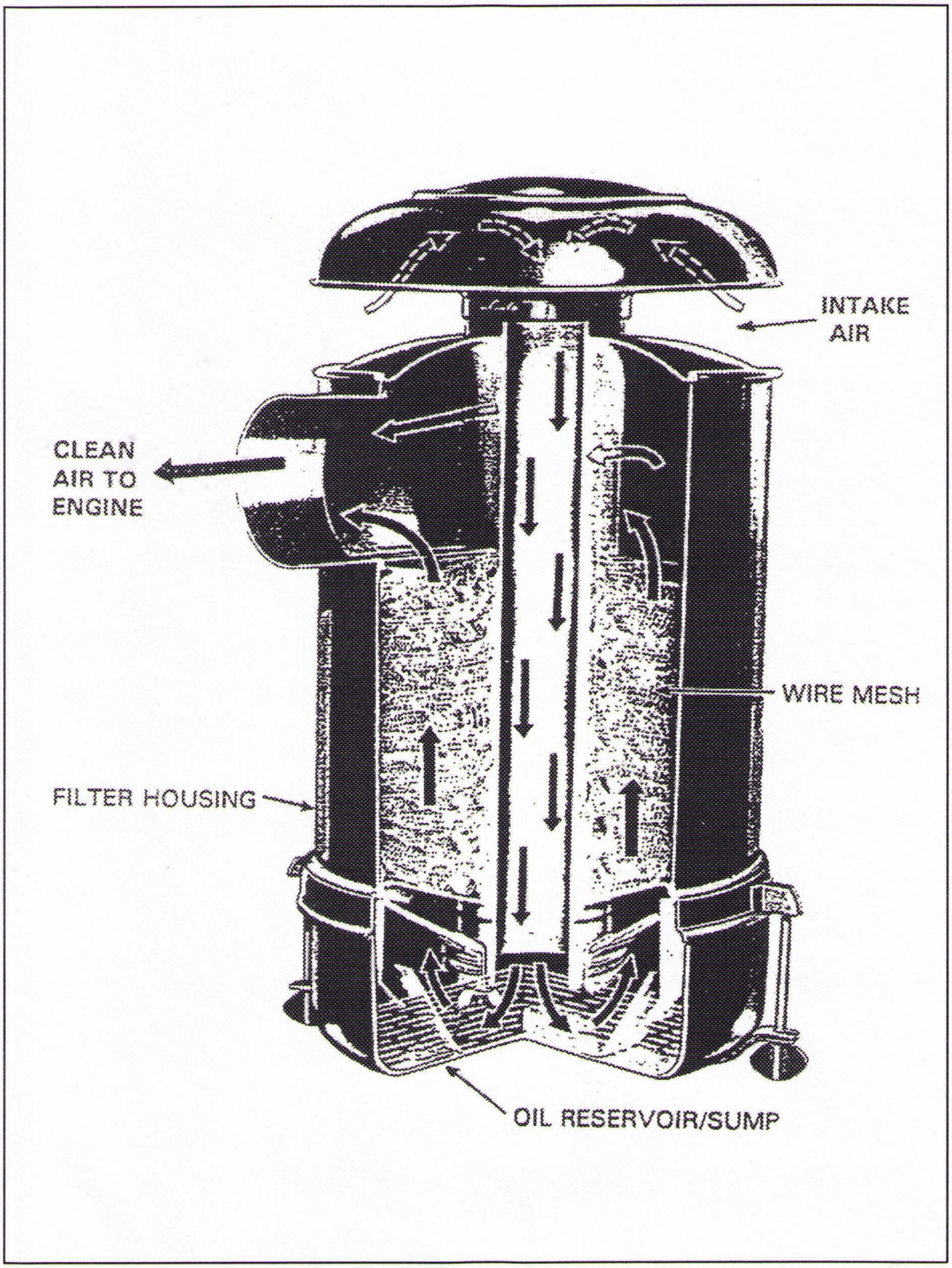


Figure 4-5 Oil Bath Air Filter

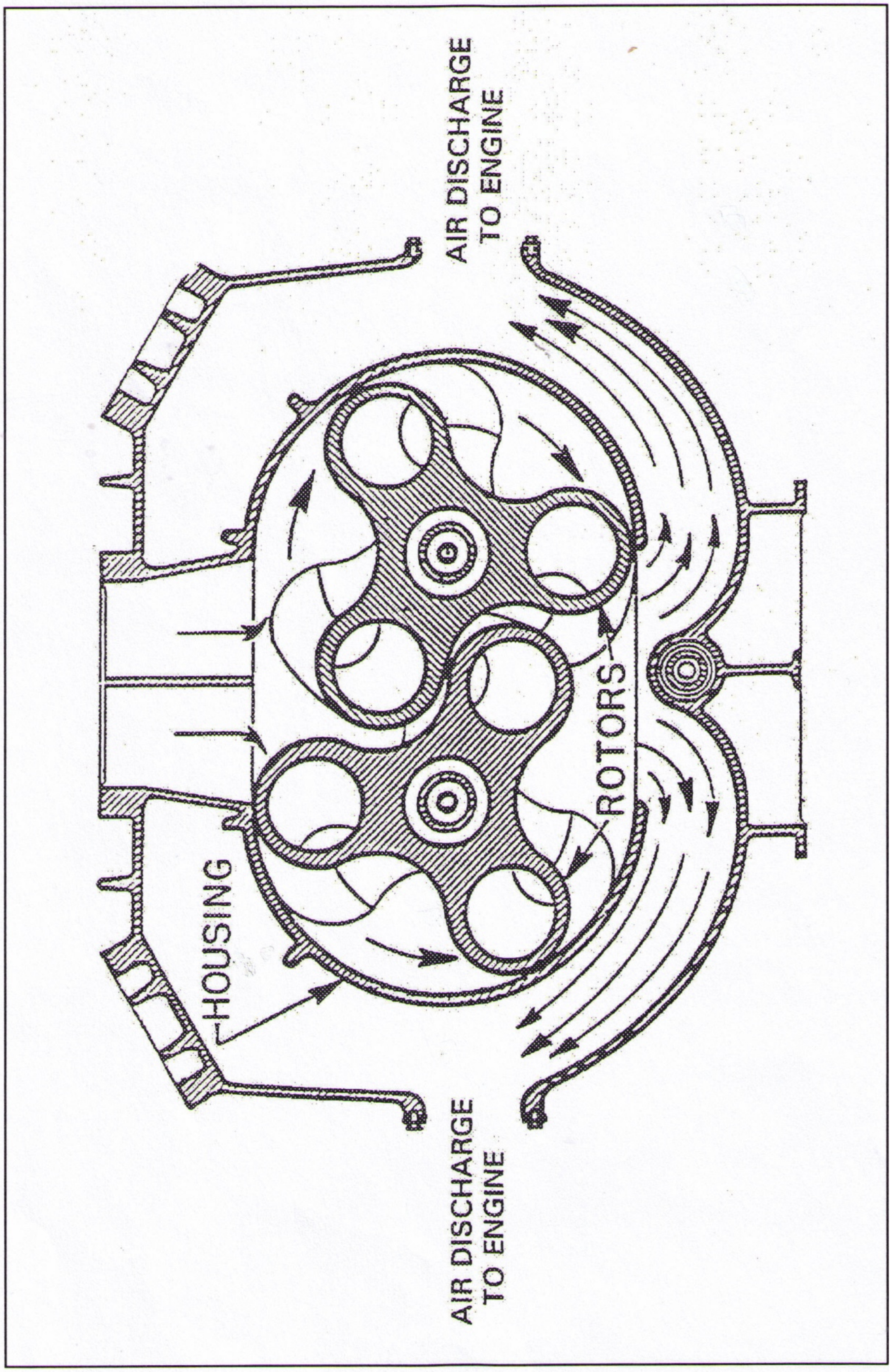


Figure 4-6 Blower/Supercharger

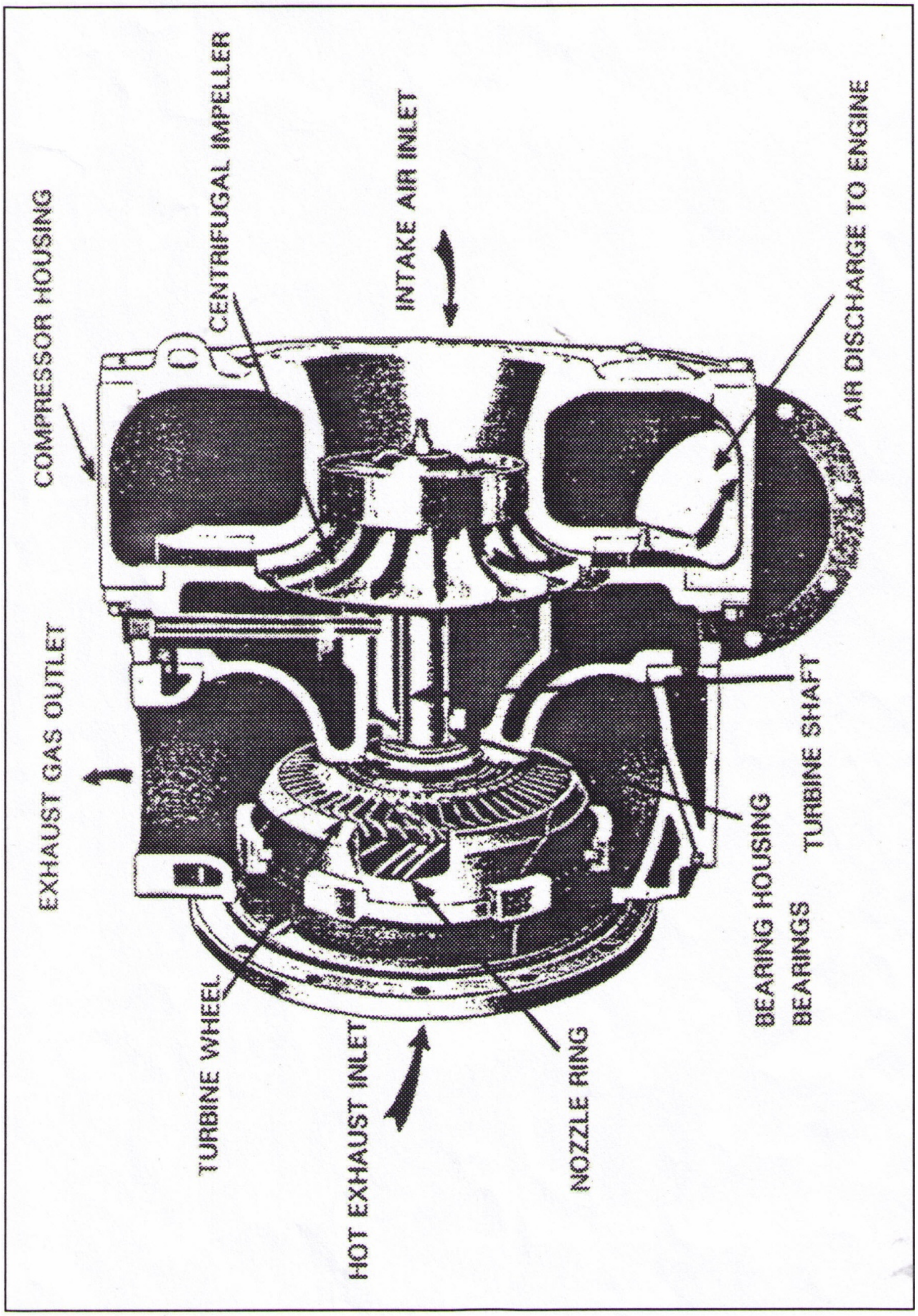


Figure 4-7 Exhaust Driven Turbocharger

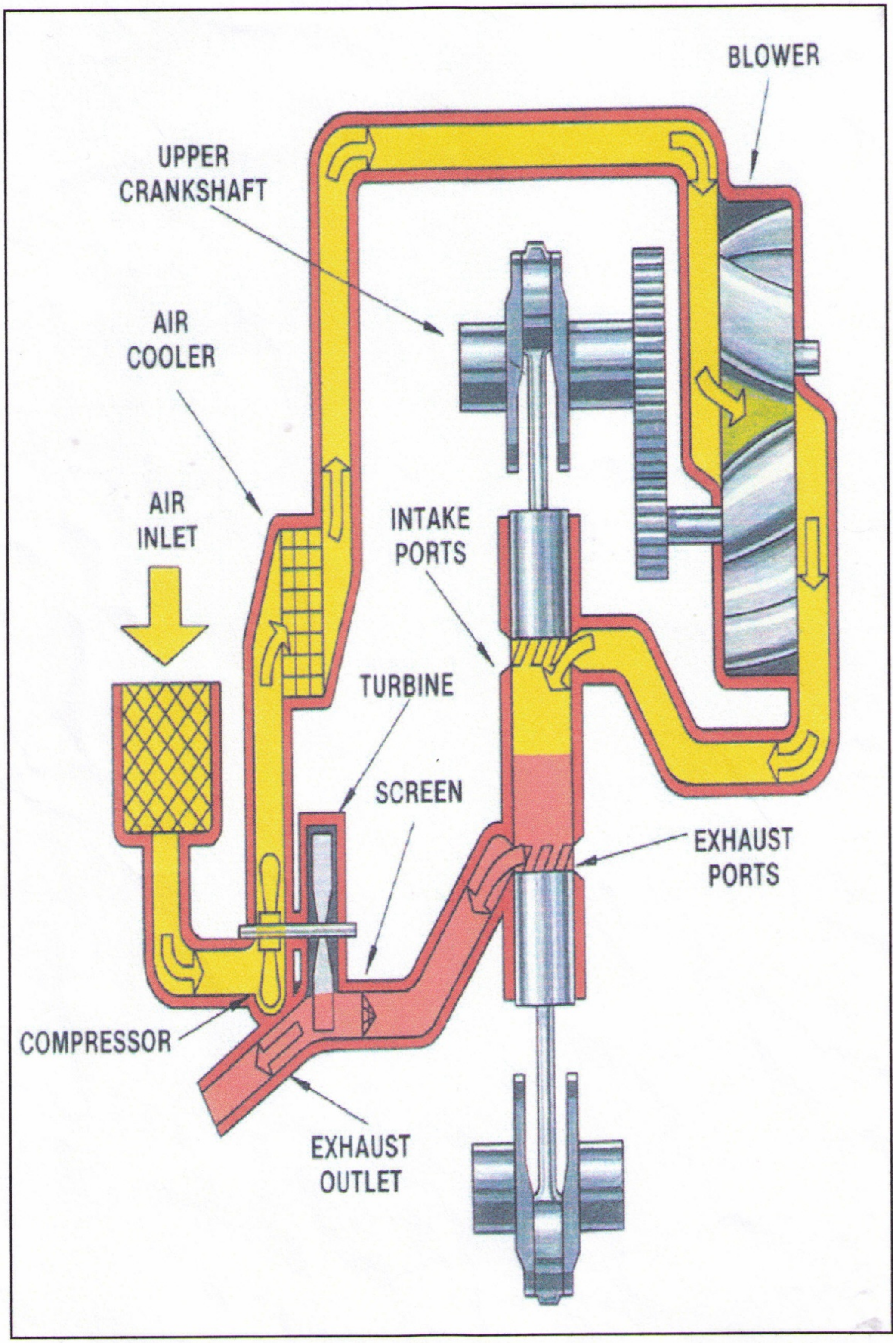


Figure 4-8 Intake Air and Exhaust Flow

Standard Conditions:

90°F ambient air, 90°F intercooler water inlet temperature, up to 4,000 feet altitude

For Ambient Temperatures		For Altitude*		For Intercooler Hx Inlet Temperatures	
Temp.	De-Rating	Altitude	De-Rating	Temp.	De-Rating
90°F	0.0%	4,000 ft	0%	90°F	0%
100°F	1.25%	5,000 ft	4%	100°F	2.5%
110°F	2.5%	7,000 ft	8%	110°F	4.0%
120°F	4.0%	10,000 ft	18%	120°F	5.0%
				140°F	8.0%

* Equivalent reductions in intake manifold pressure below standard whether due to altitude or engine degradation would require de-rating.

Figure 4-9 Typical Diesel Generator Basis for Ratings/DEMA Ratings

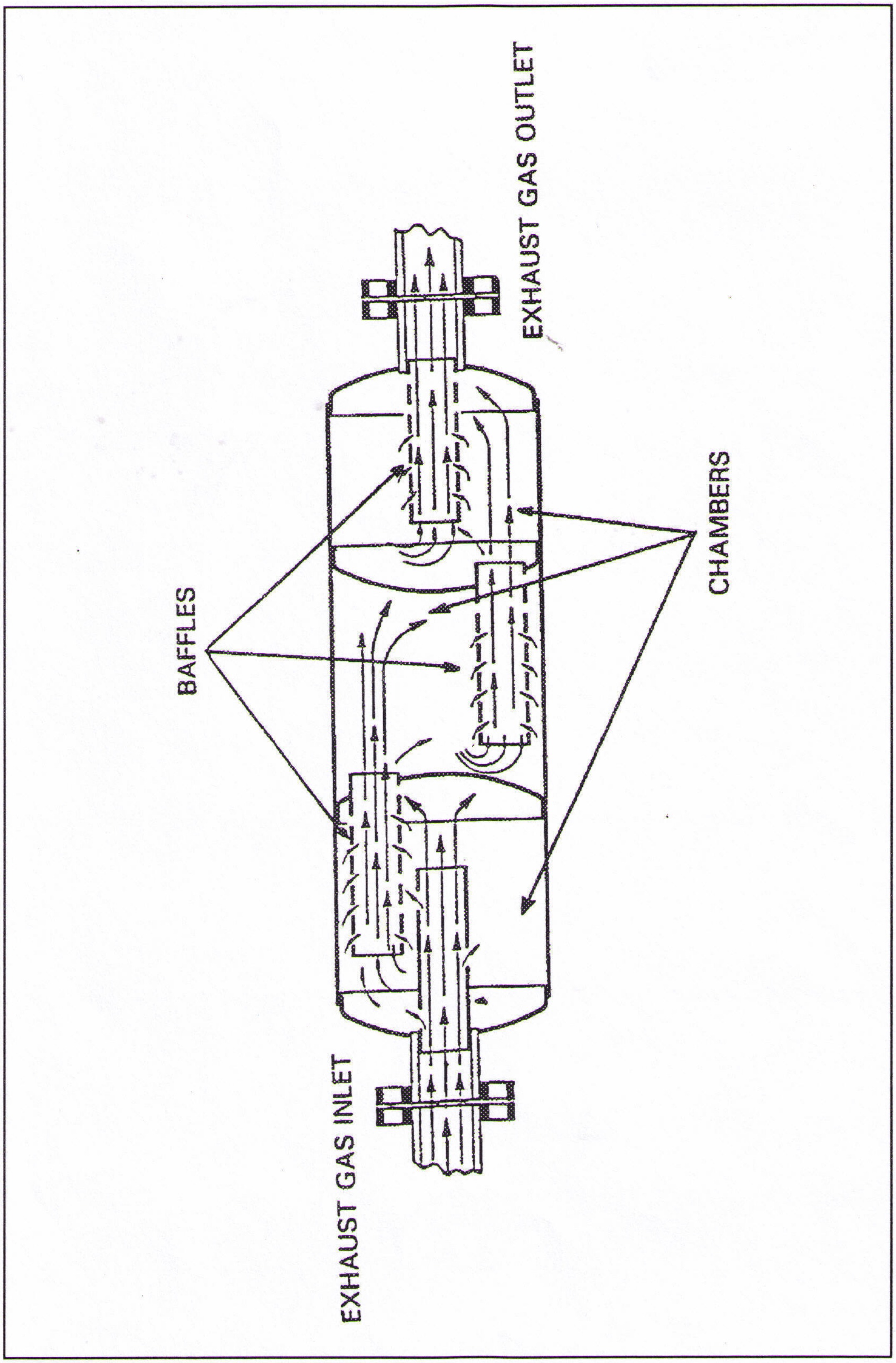


Figure 4-10 Exhaust Gas Silencer

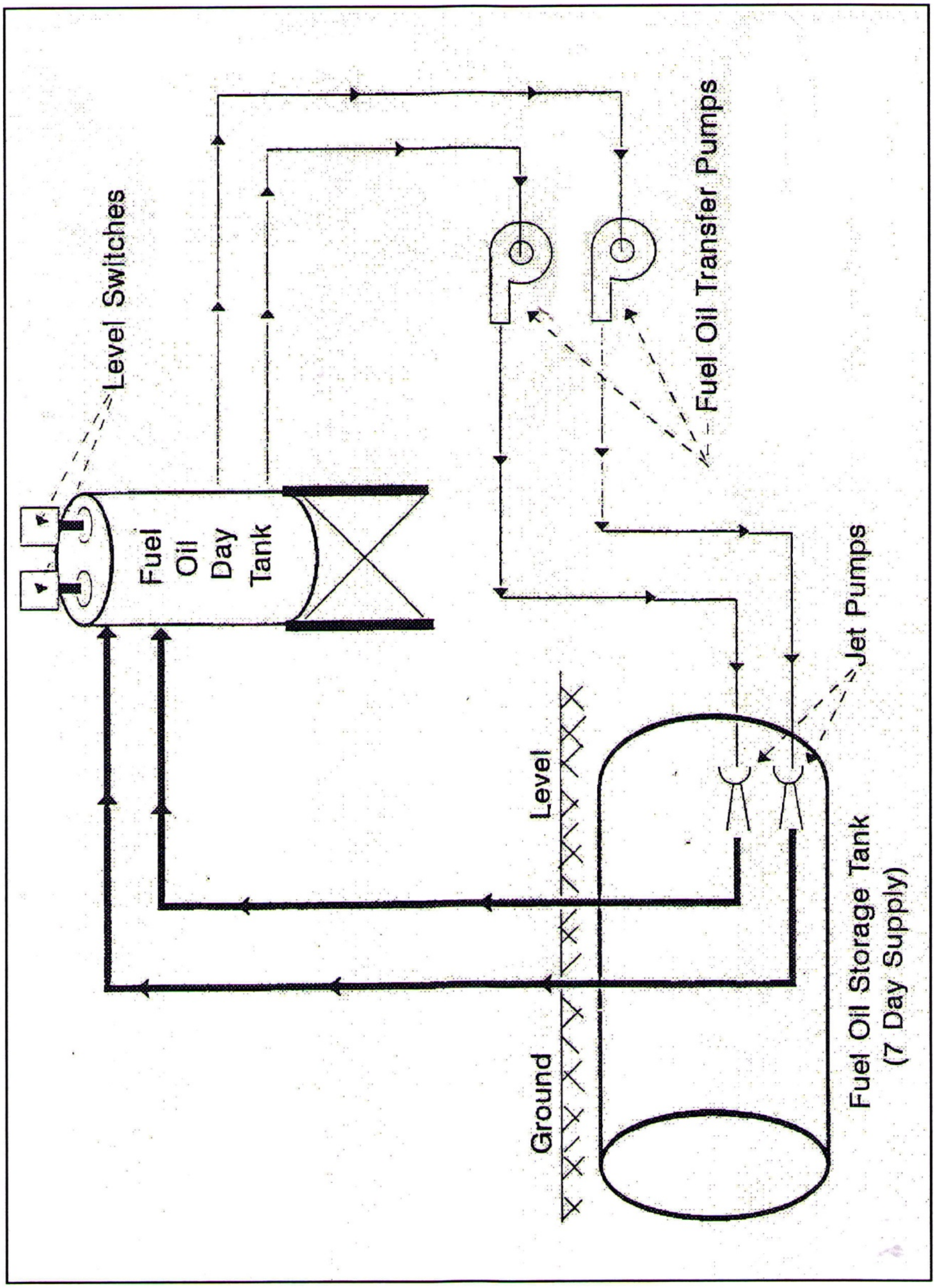


Figure 4-11 Fuel Oil Storage and Transfer System

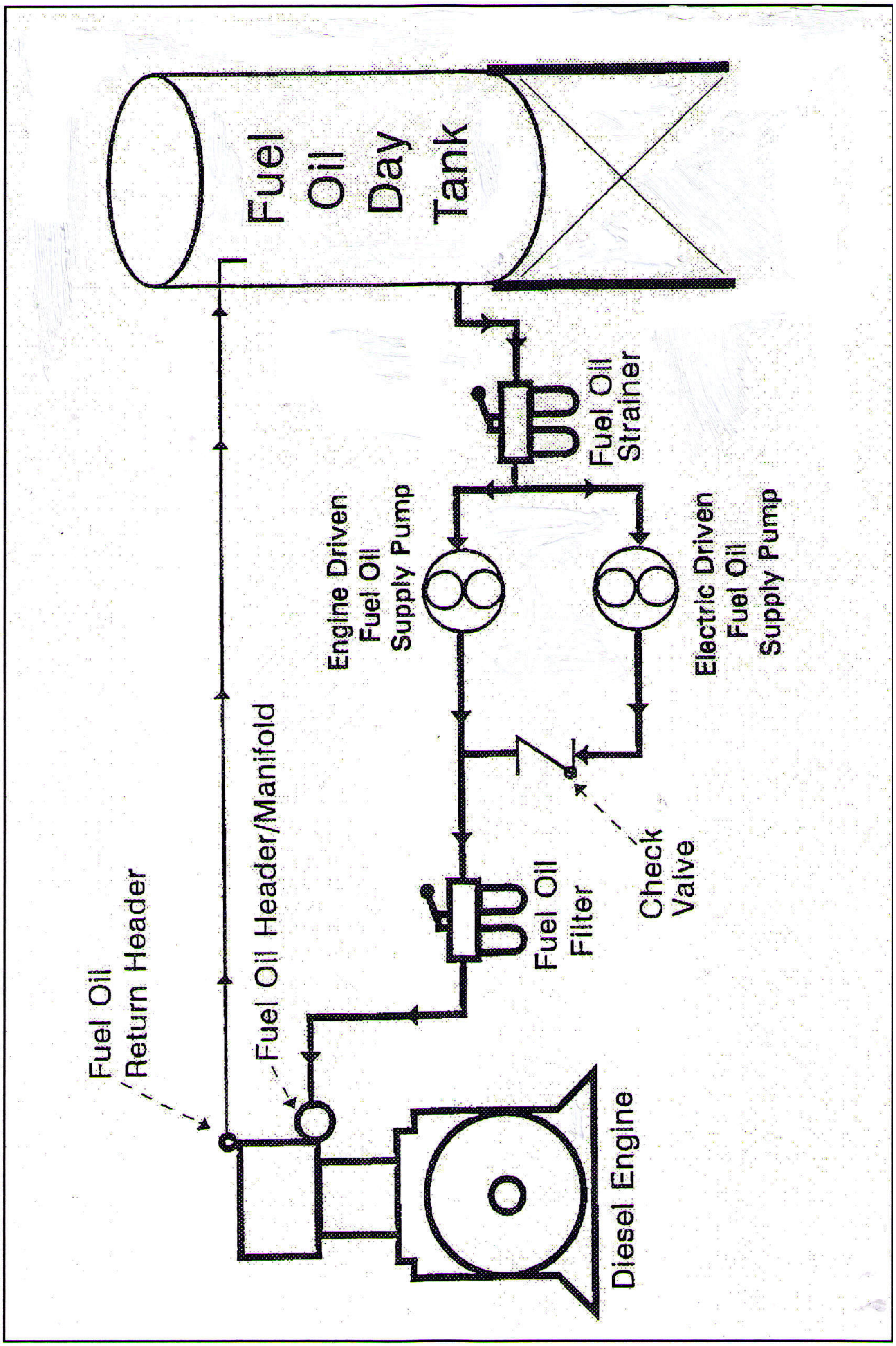


Figure 4-12 Fuel Oil Supply System

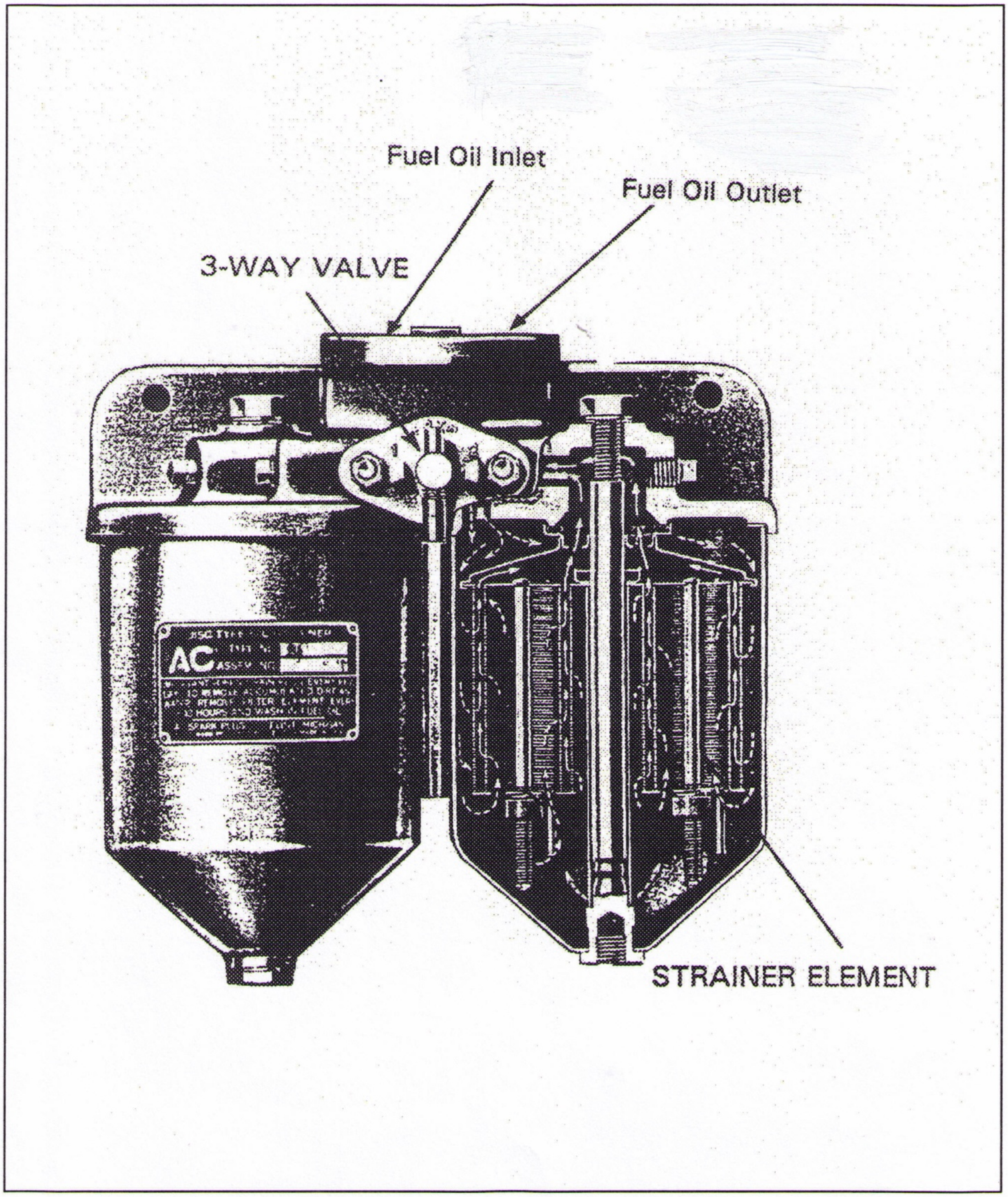


Figure 4-13 Fuel Oil Strainer

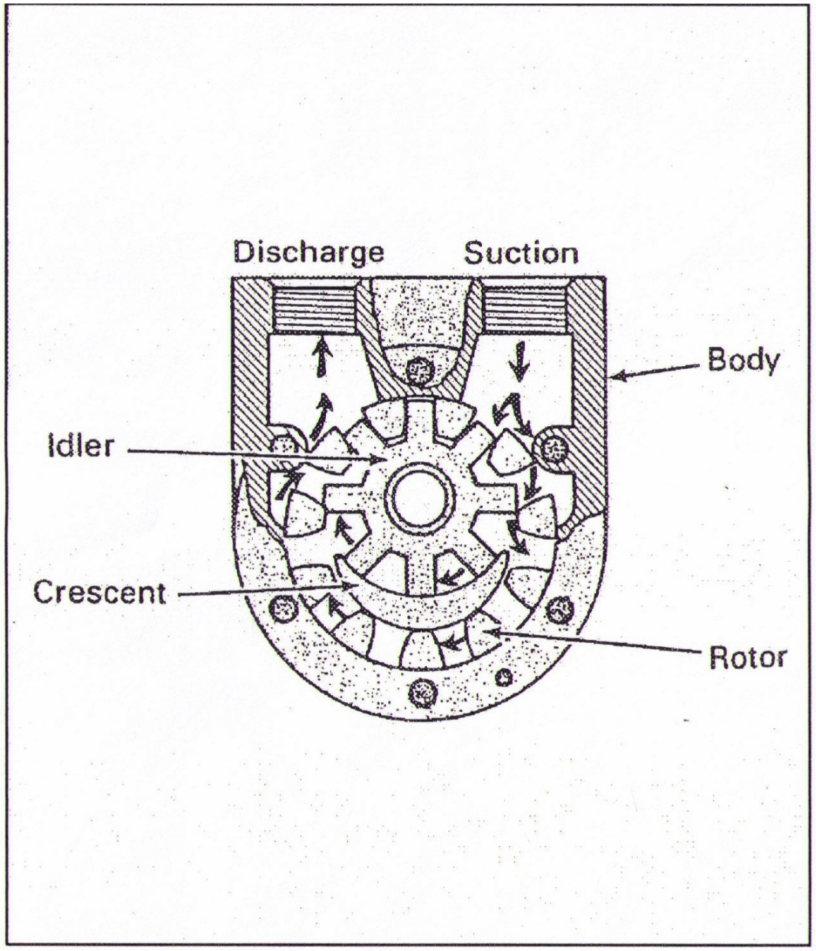


Figure 4-14 Fuel Oil Supply Pump

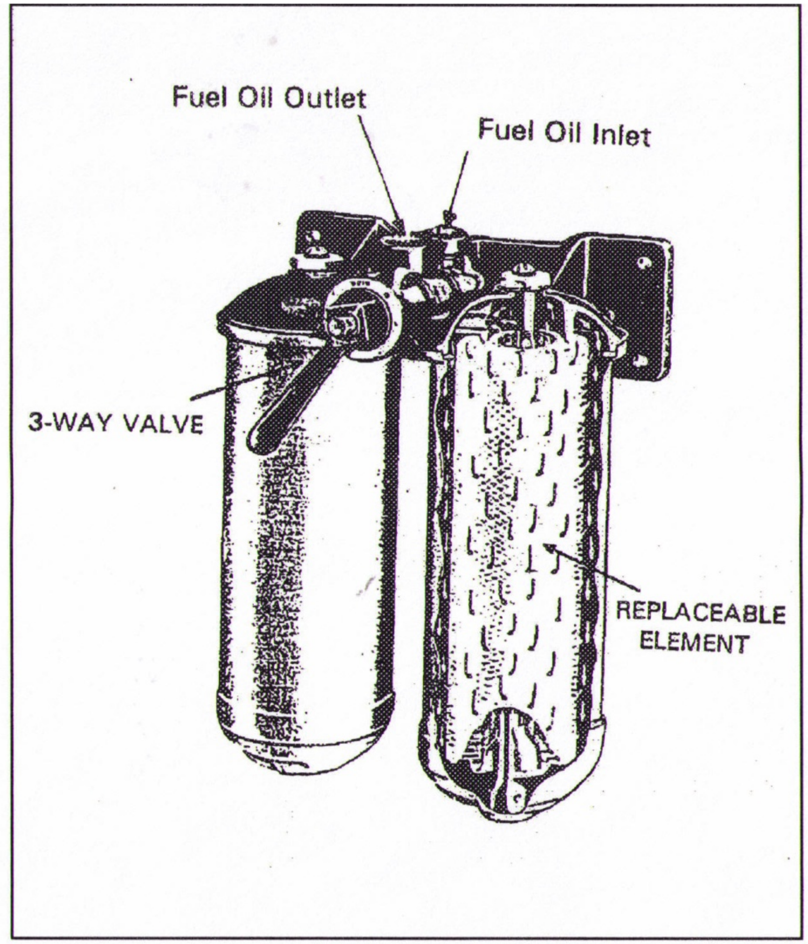


Figure 4-15 Fuel Oil Filter

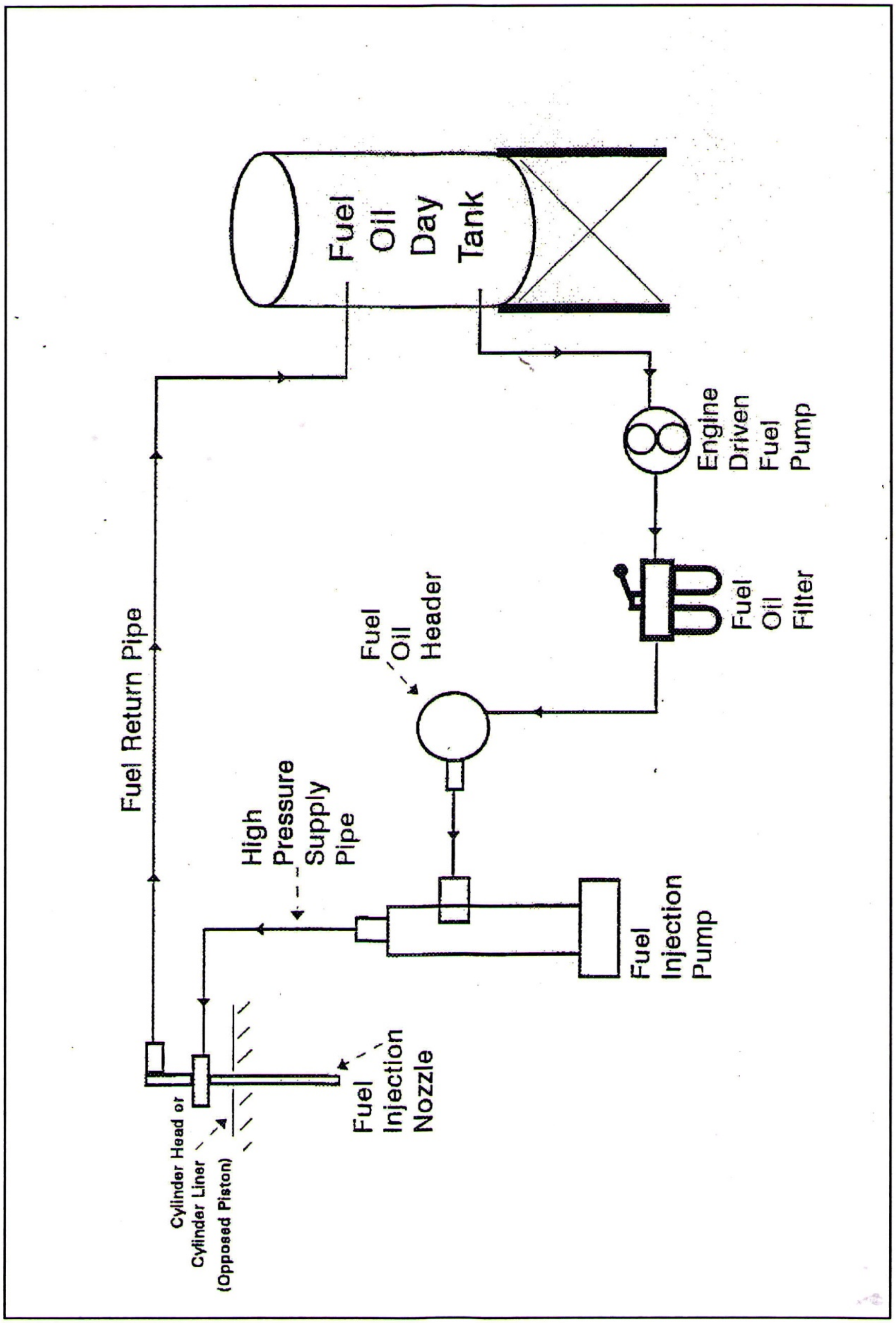


Figure 4-16 Pump and Nozzle System

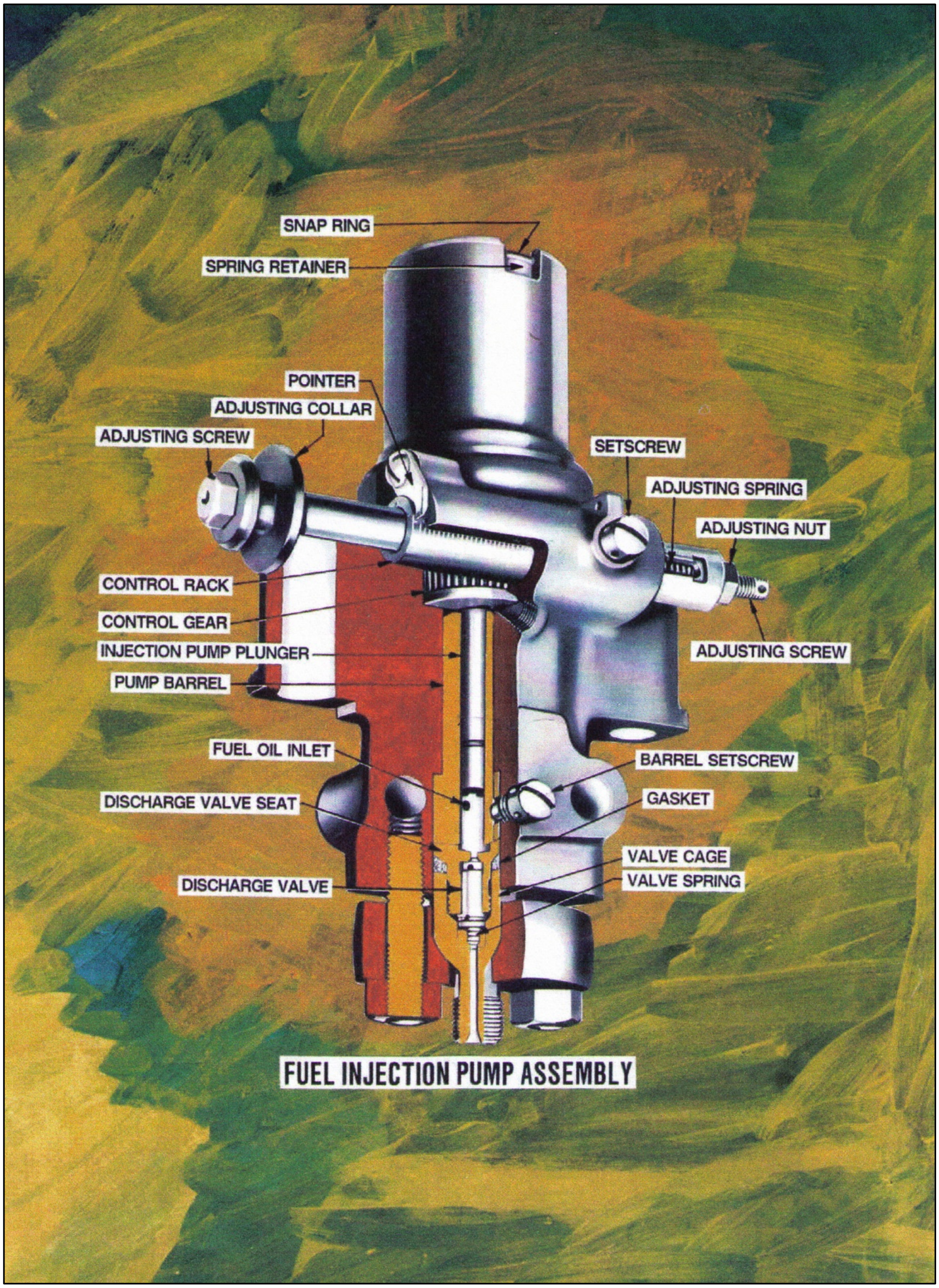


Figure 4-17 FM OP Engine Injection Pump Construction

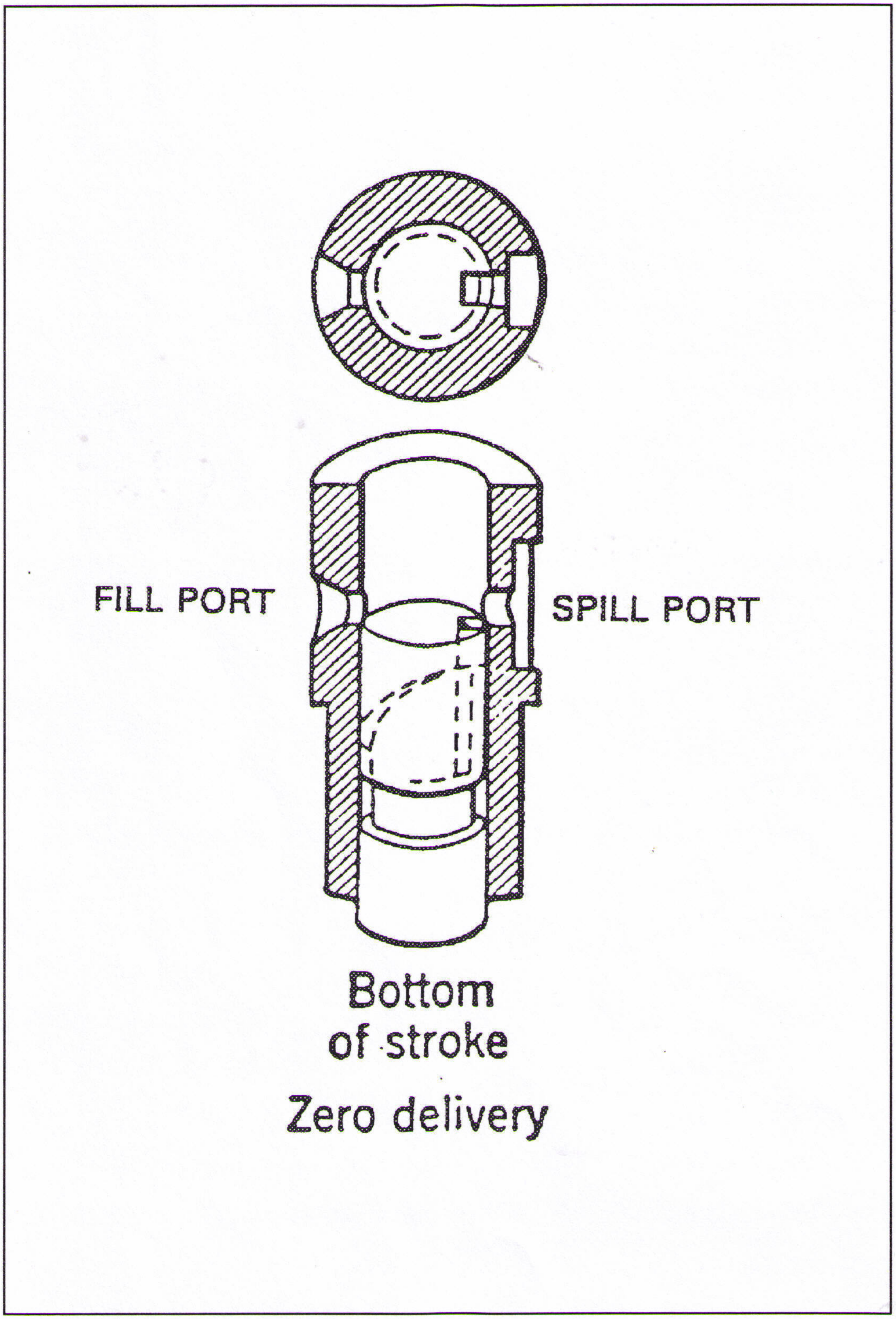


Figure 4-18 Zero Fuel Delivery

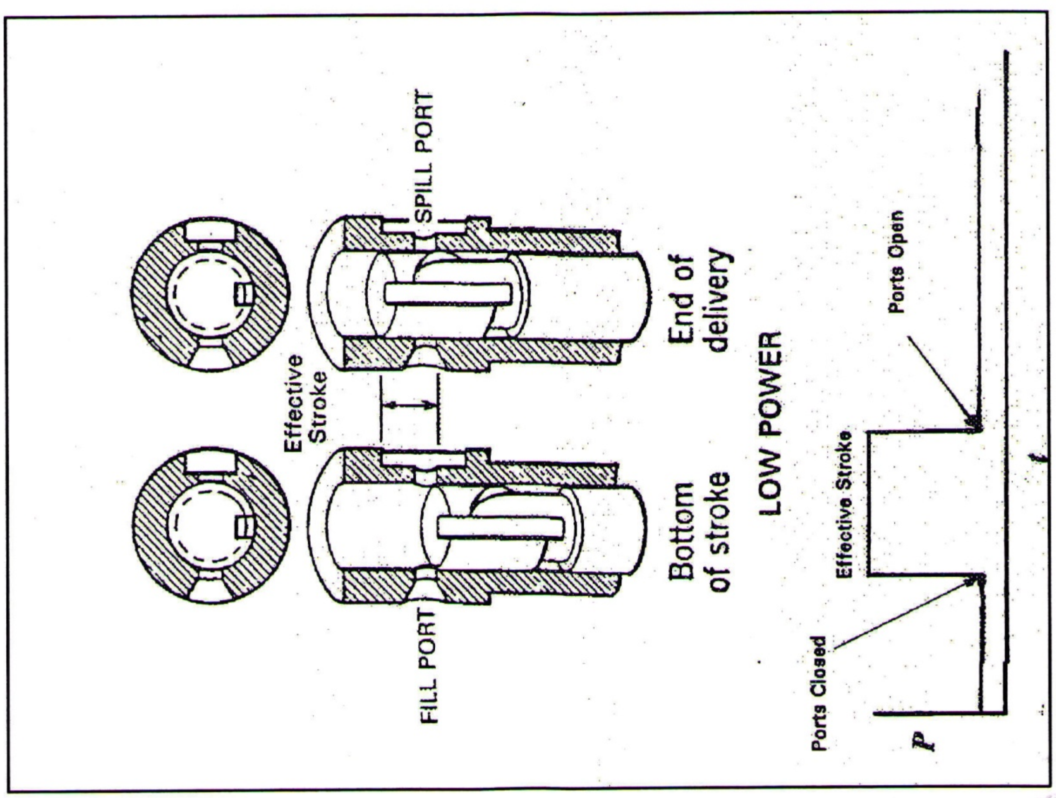


Figure 4-19 Low Power

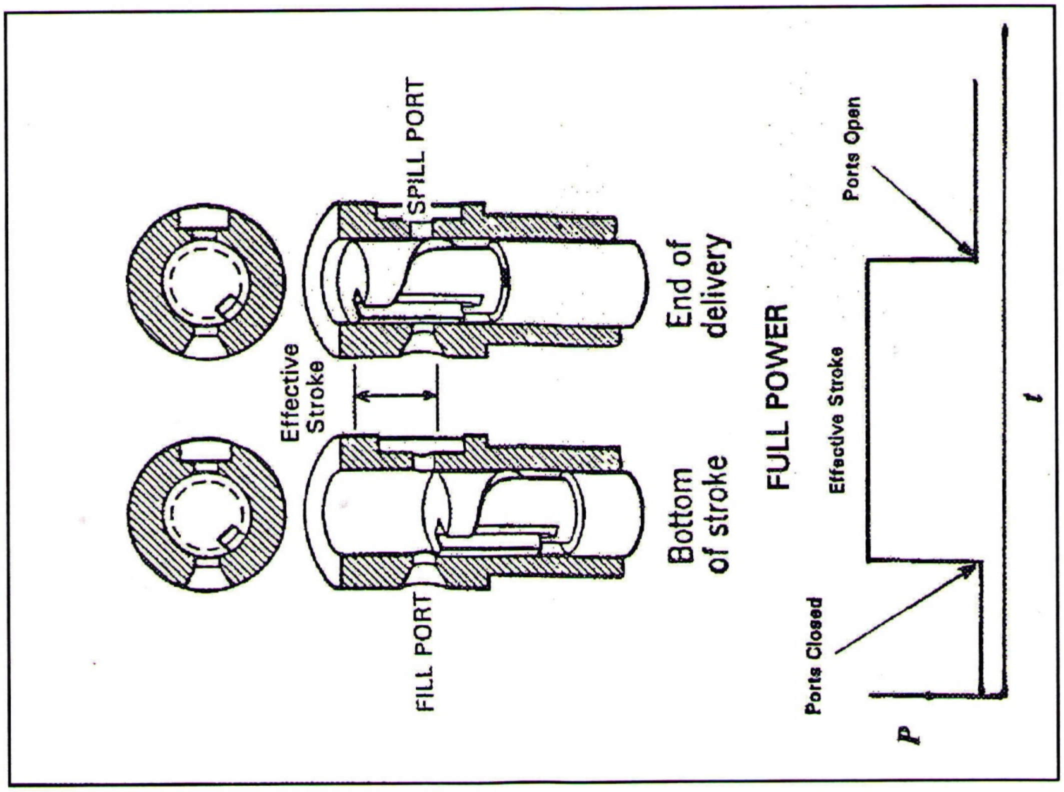


Figure 4-20 Full Power

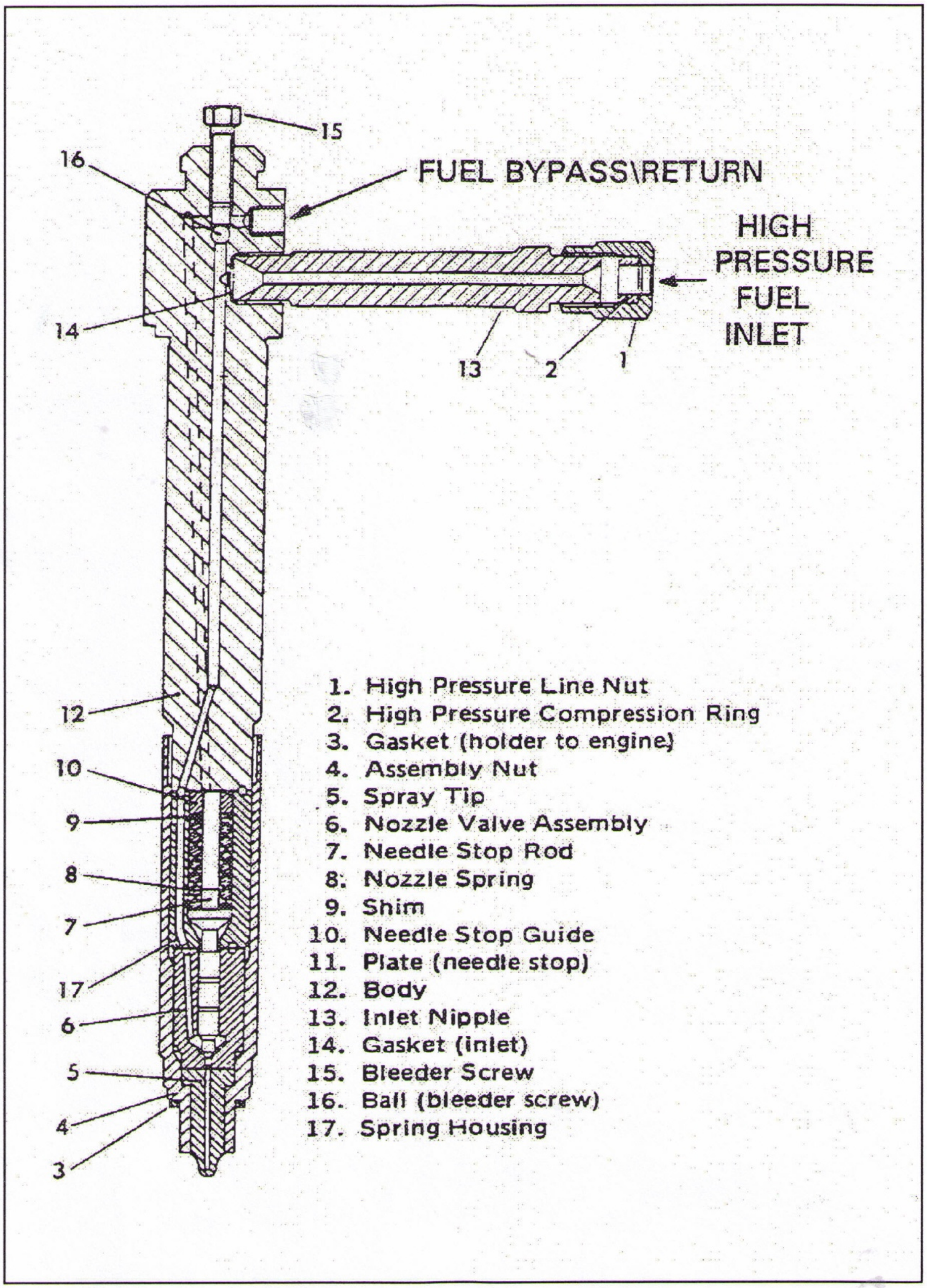


Figure 4-21 Injection Nozzle

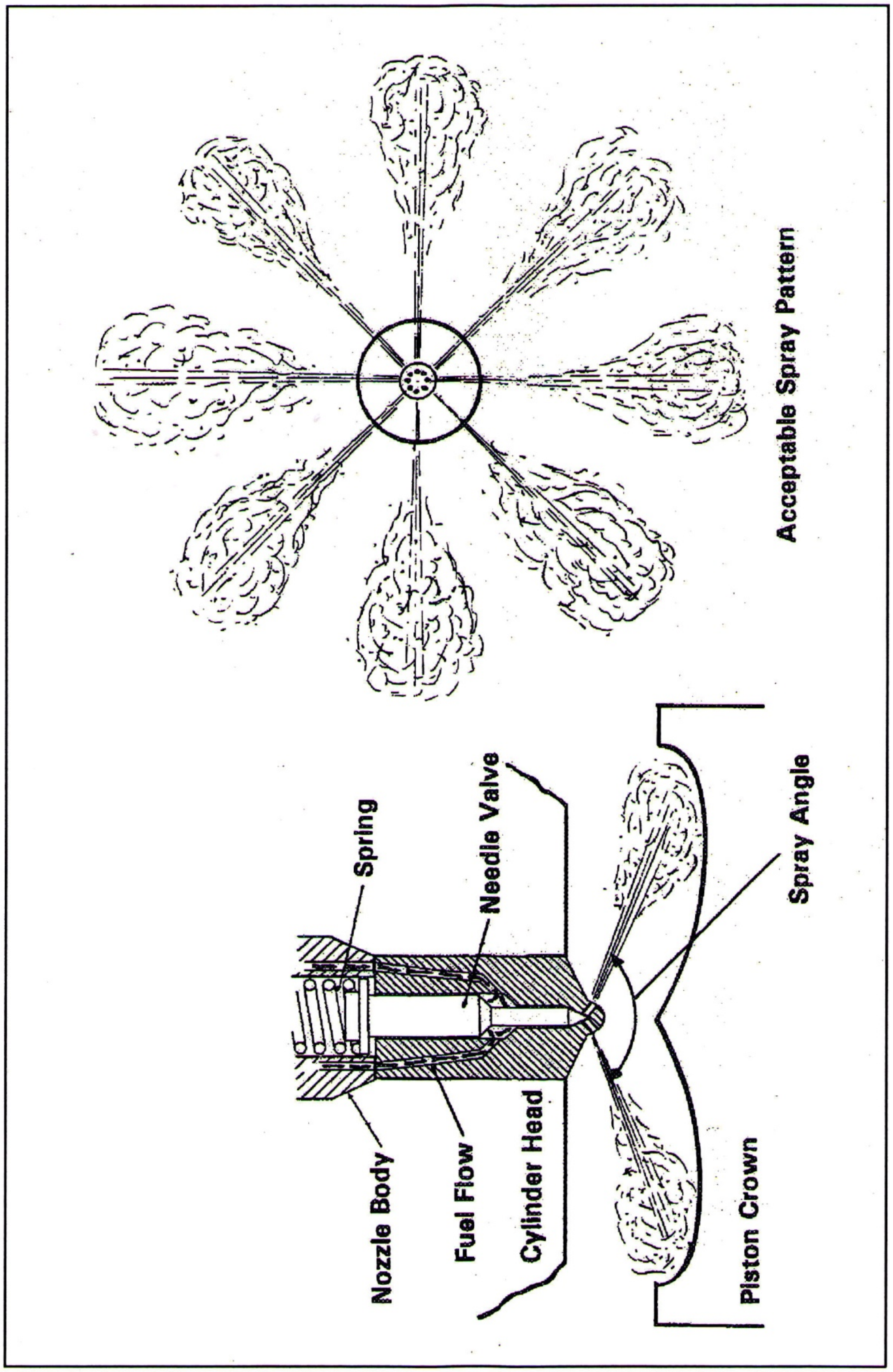


Figure 4-22 Injection Nozzle Spray Pattern

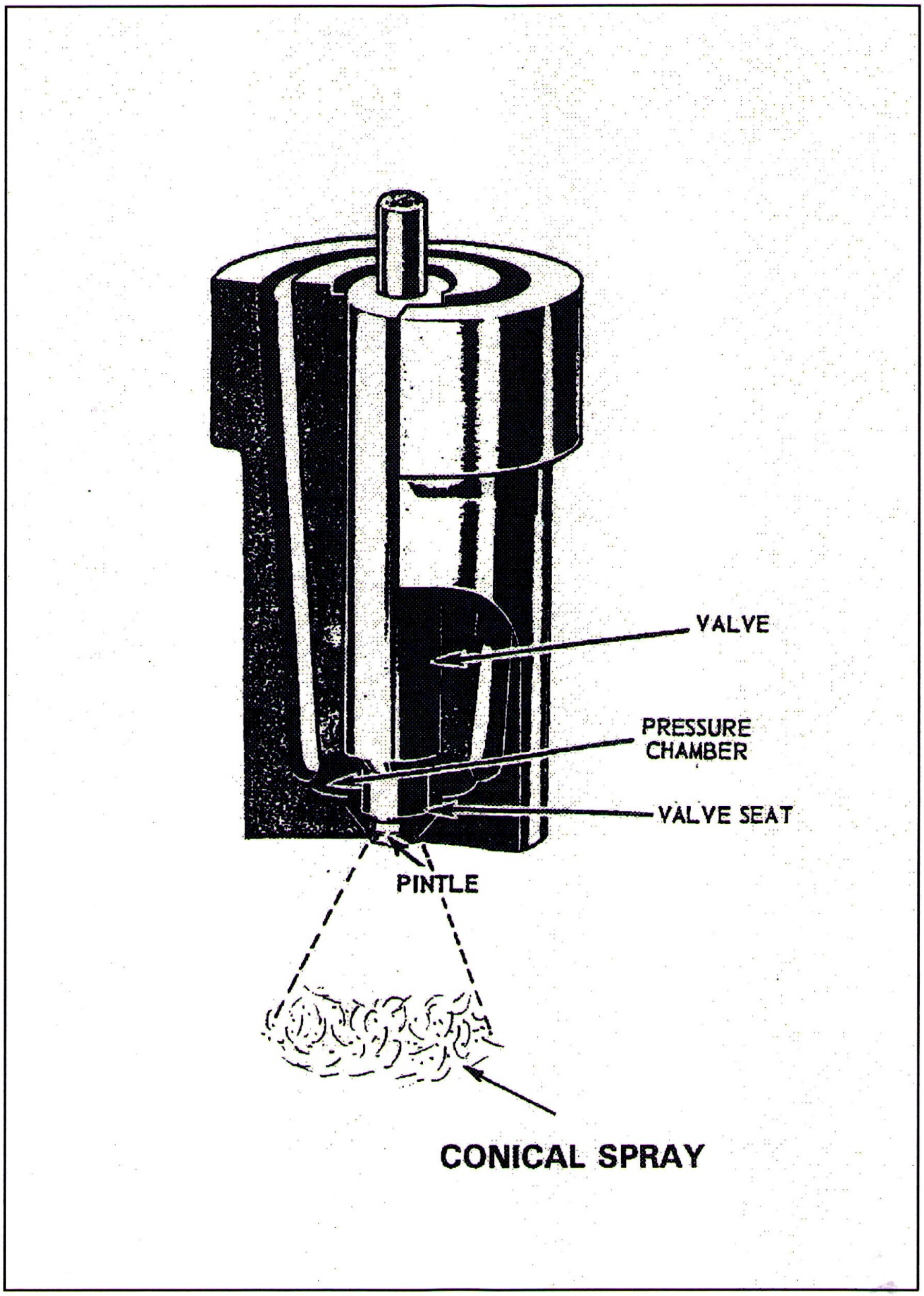


Figure 4-23 Pintle Nozzle

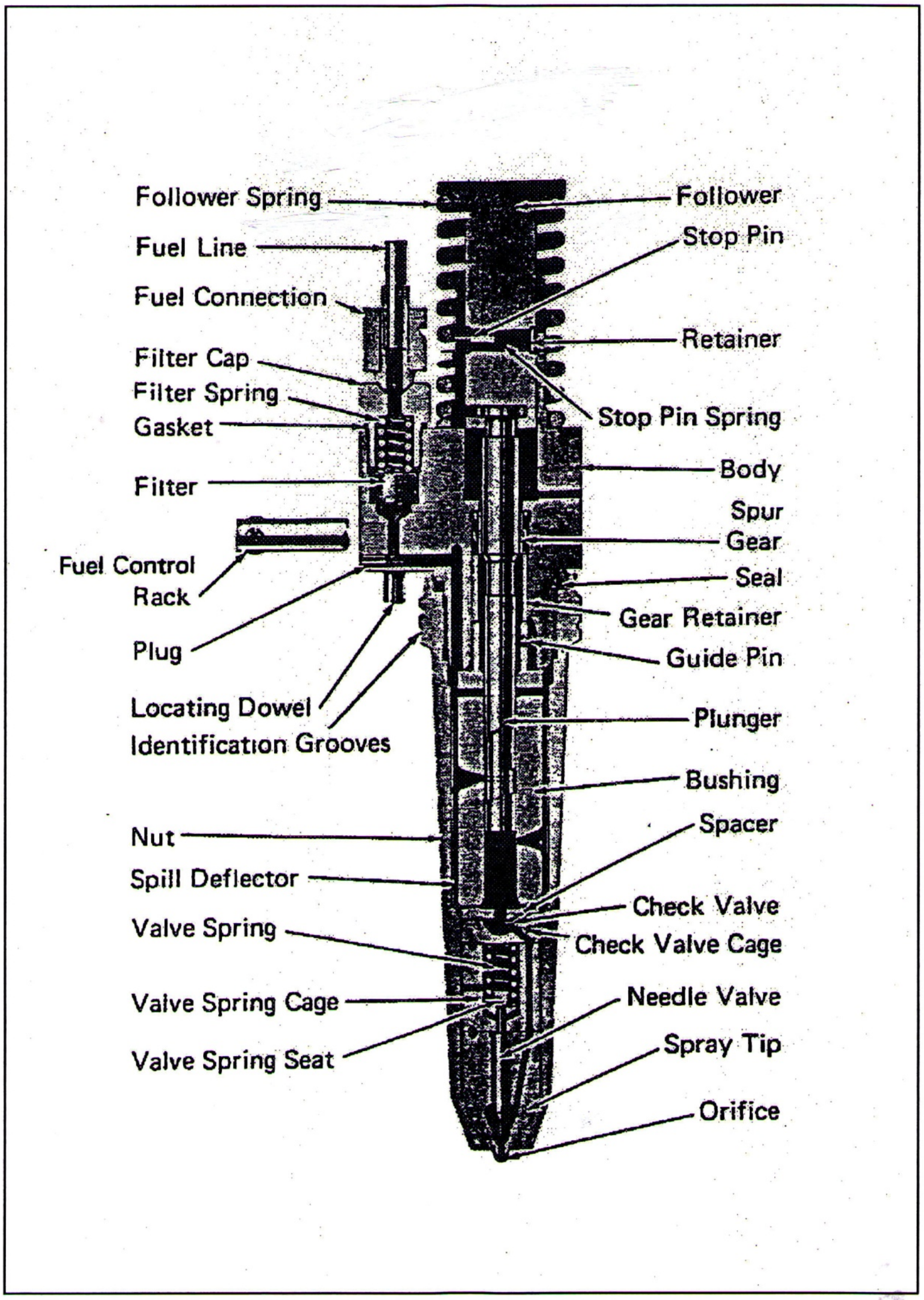


Figure 4-24 Unit Type Fuel Injector

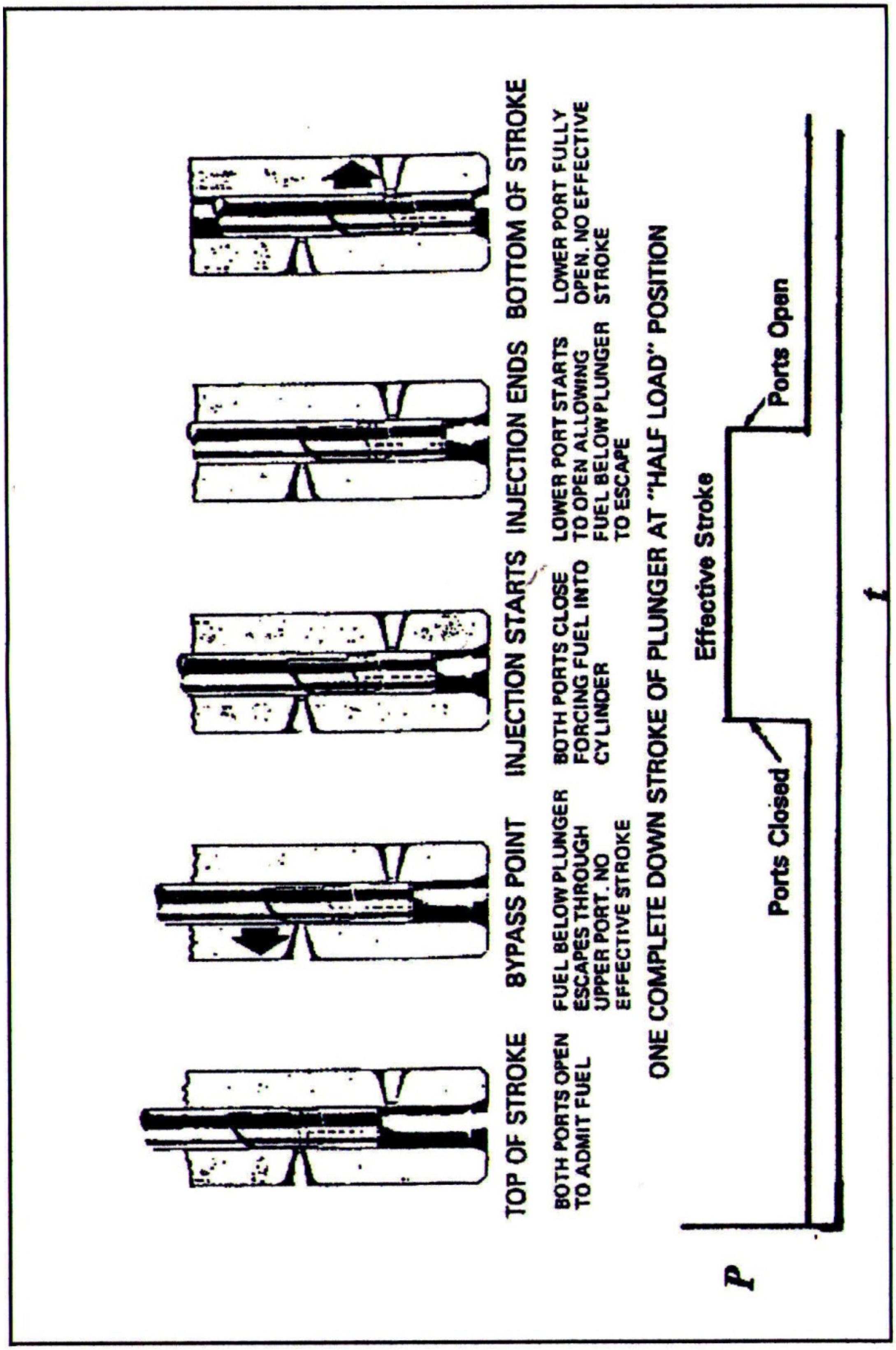


Figure 4-25 Injector Operation

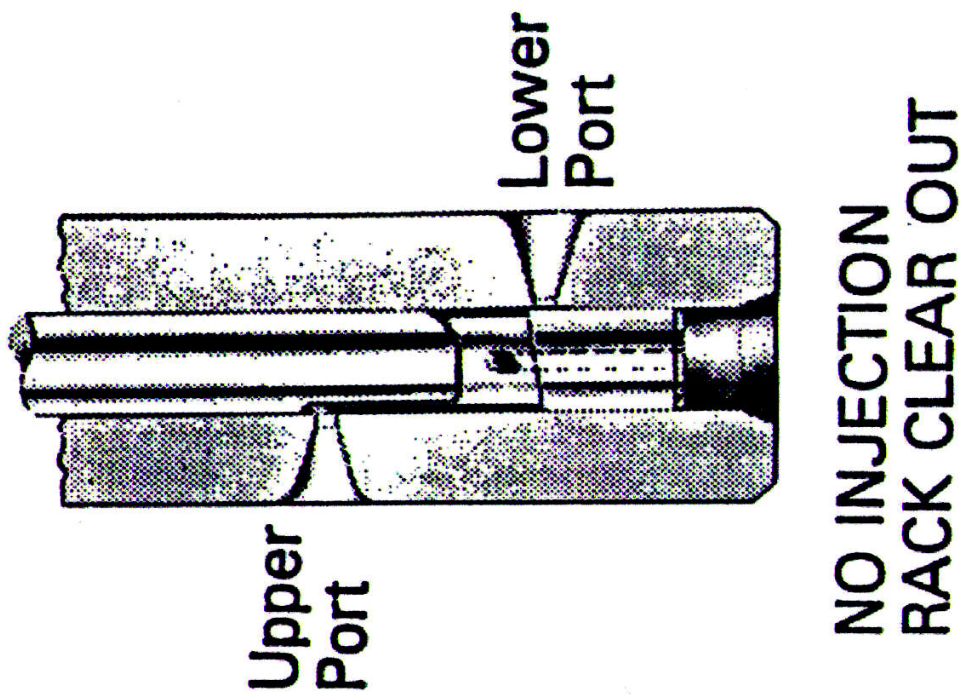


Figure 4-26 Zero Fuel Delivery

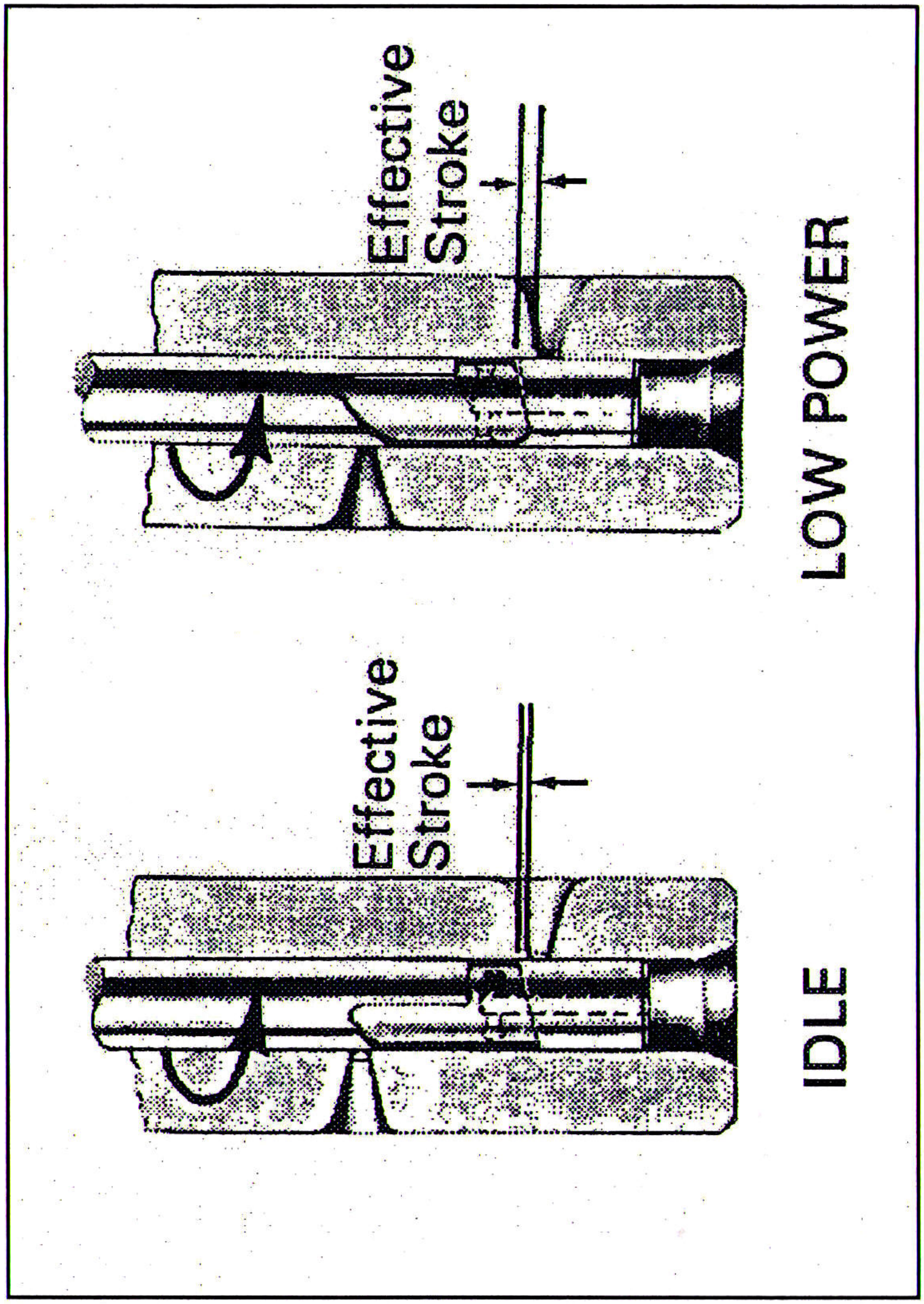


Figure 4-27 Low Power

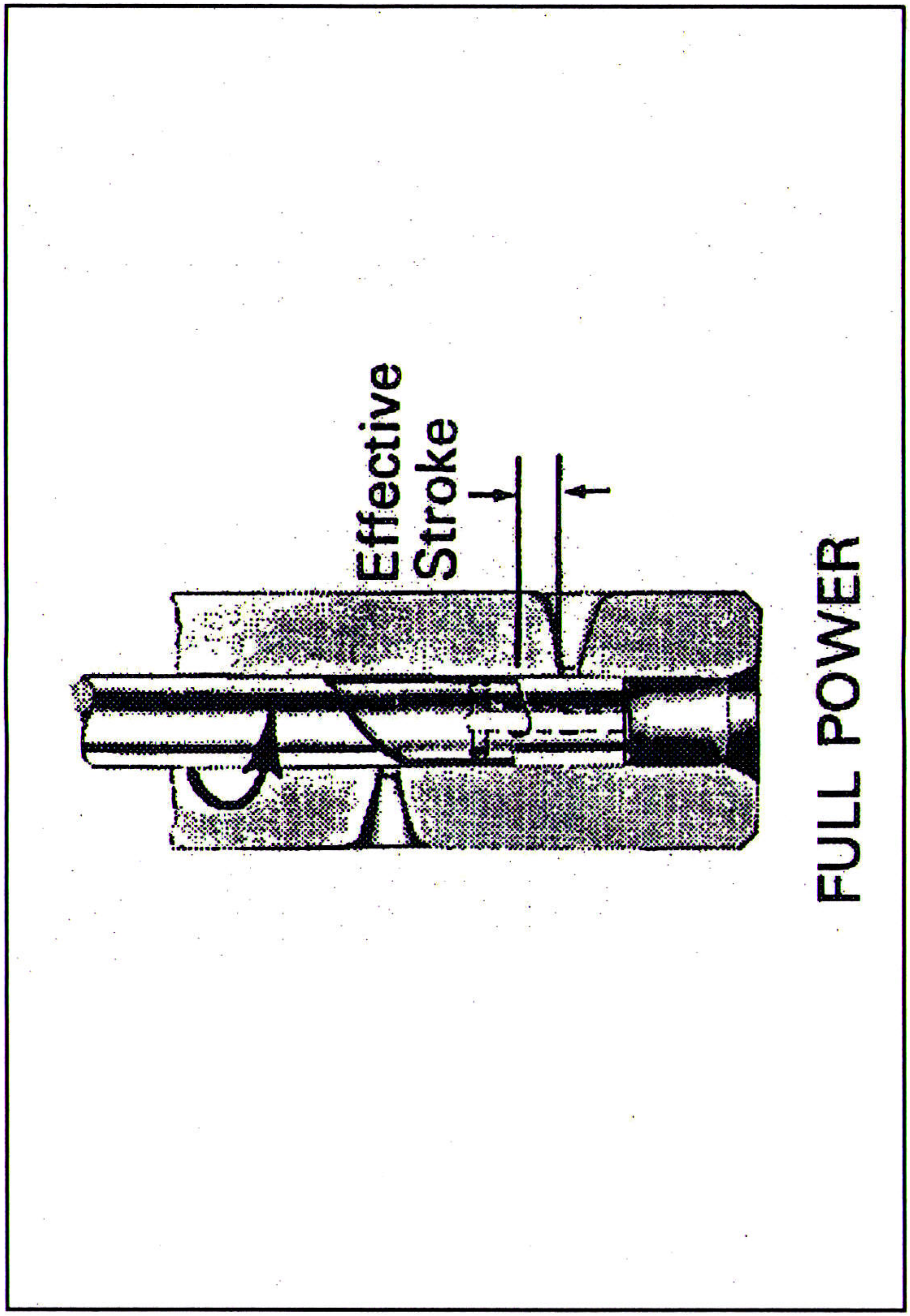


Figure 4-28 Full Power

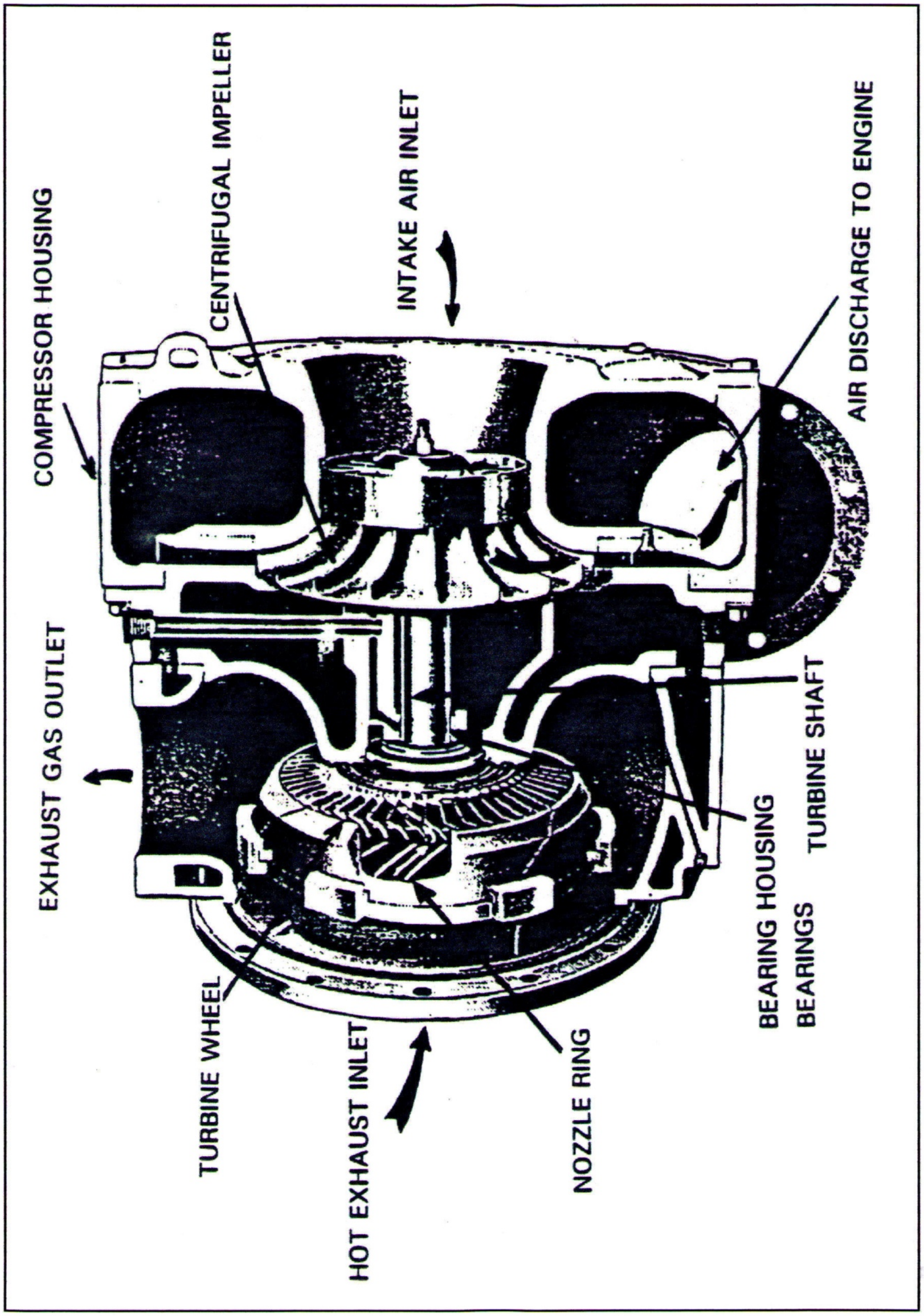
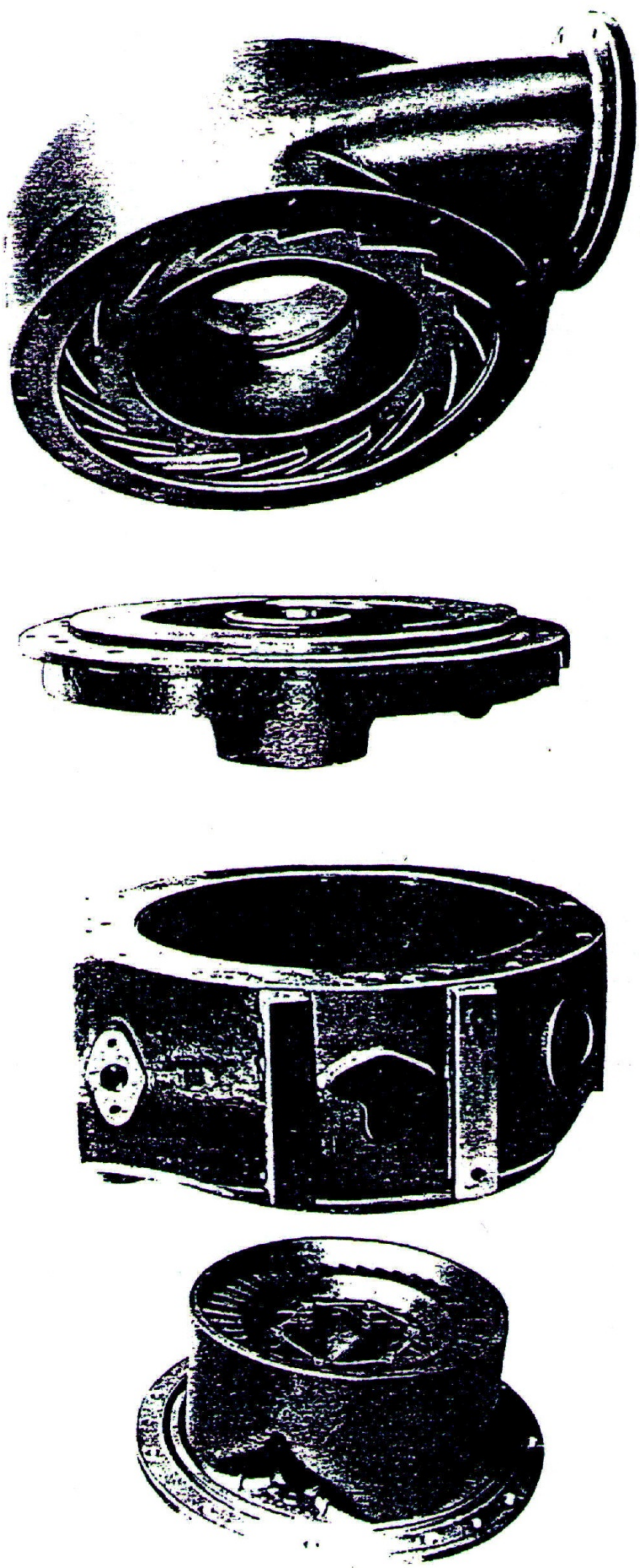


Figure 4-29 Turbocharger Cutaway Section



—Left to right: Inlet Casing Assembly, Turbine Casing, Intermediate Casing, Blower Casing Assembly.

Figure 4-30 Casing Assemblies

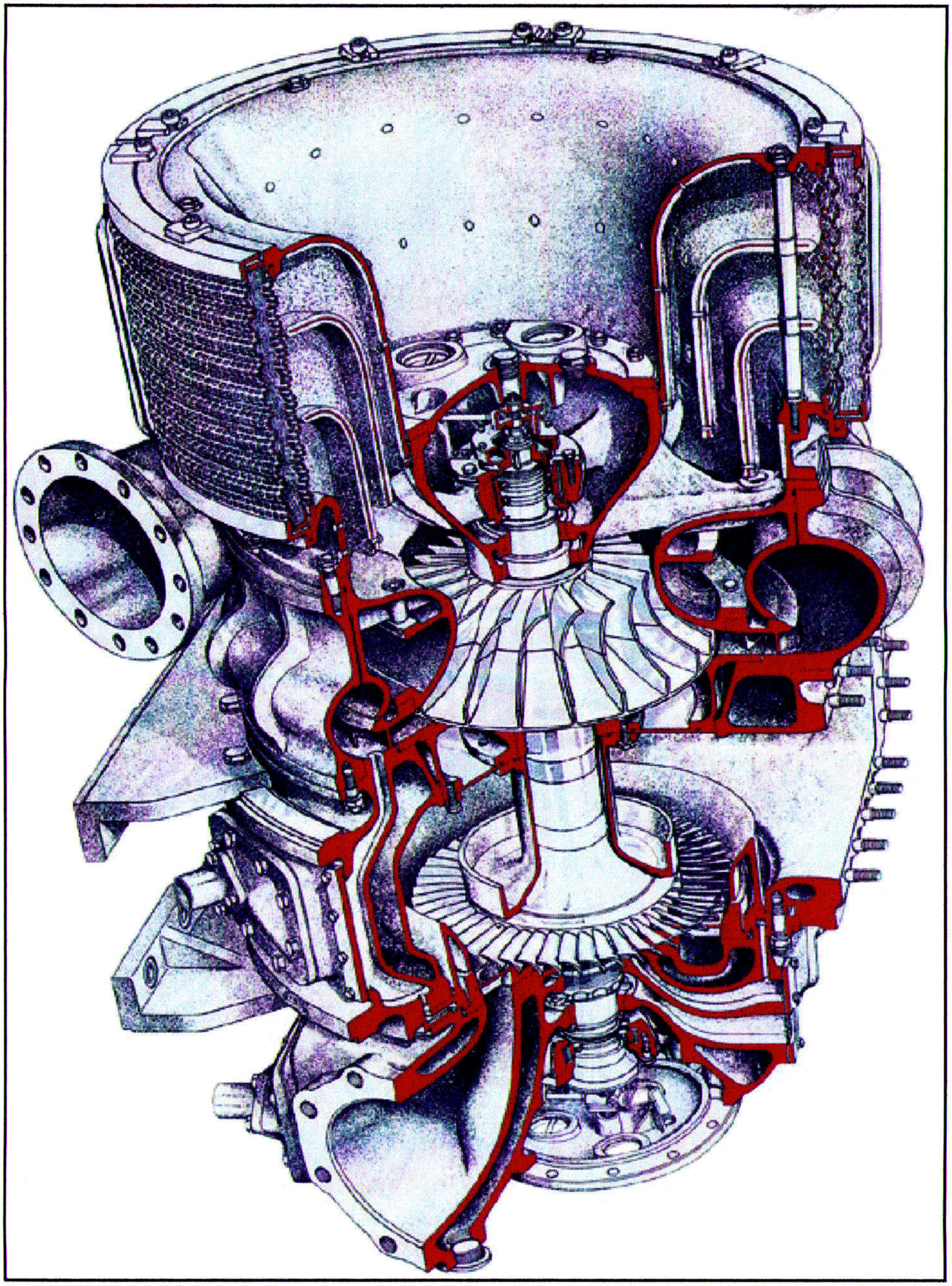


Figure 4-31 Brown and Boveri Turbocharger

HANDS-ON SESSION 5

5.0 COMBUSTION AIR TURBOCHARGERS AND SCAVENGING BLOWERS

Purpose

This session's purpose is to complement the classroom instruction of Chapter 4.

Learning Objectives

Upon completion of this lesson you will be able to:

- Understand the basic components and assemblies that make up the engine turbocharger, their assembly, and their functions.

- Gain more knowledge from instructor presentation of the cutaway scavenging blower.

5.1 Turbochargers

The purpose of the turbocharger is to provide air to the engine for combustion. Before turbocharging became common, most engines of the 4-stroke cycle design were naturally aspirated. That is, the air was ‘breathed’ into the cylinder by the action of the piston sucking the air into the engine. This resulted in the air in the cylinder being slightly below atmospheric pressure and as a result, the air was less dense and contained less oxygen than normal air. Because the engine is dependent on the amount of oxygen to burn the fuel, the engine’s output was restricted. By using a turbocharger, more air/oxygen is pumped into the cylinder at positive pressure. Therefore, the engine is capable of burning more fuel and putting out more power.

The same general principle applies to the 2-stroke cycle engine as well. The normal scavenging air blower output capacity was restricted by the engine output horsepower to drive it. Turbocharging a 2-stroke cycle engine considerably increases the power output capability without an increase in the horsepower to drive the blower since the energy to drive the turbocharger is derived from waste energy in the engine exhaust.

While it does cost some energy for the engine to overcome the increased exhaust back pressure required to drive the turbocharger, the net effect of the increased combustion air supply to the engine far outweighs the slight increase in the horsepower required to overcome the increase in exhaust back pressure. Turbocharged engines are more efficient than blower-scavenged or naturally-aspirated engines, thus proving that turbo-charging assists the engine’s power output.

The turbocharger consists of five basic parts. See Figures 4-29 and 4-30.

1. The rotating assembly consisting of the turbine and the compressor mounted on a common shaft.
2. A center housing that holds the bearings that support the rotating assembly.
3. The compressor housing with its diffuser ring.
4. The exhaust casing which surrounds the turbine end of the rotating assembly.
5. The exhaust inlet casing with its nozzle ring to direct flow to the turbine blades.

On most of the turbochargers made by American manufacturers, the bearings are within the center housing and the lube oil supply is from the engine lube oil system. In most turbochargers of European manufacture, the bearings are outboard of the turbine and compressor wheels and the oil is supplied from sumps within the turbocharger assembly and there is a self contained lube oil pump. See Figure 4-31. There are examples of these differing constructions available for the students to study in the work areas.

With directions from the instructor, students will disassemble a typical OP turbocharger by using the following procedure:

1. Remove the bolts holding the exhaust inlet casing to the exhaust housing and remove the exhaust inlet casing.

2. Remove the bolts holding the exhaust housing to the center (bearing) housing and remove the exhaust housing section.

3. Remove the bolts holding the air inlet casing to the air compressor housing and remove the inlet casing.

4. Remove the bolts holding the air compressor housing to the center housing and remove the compressor casing.

5. This leaves the rotating assembly supported by the center (bearing) housing. Remove the nut at the compressor end of the rotating assembly and use a puller for removing the compressor wheel from the rotating shaft. When the compressor wheel has been removed, then pull the shaft with the turbine wheel, from the bearing housing.

6. Inspect the bearings, including the thrust bearing surfaces.

While the turbocharger is disassembled, inspect the nozzle ring for signs of damage and the presence of piston ring parts or other debris. Also inspect the compressor wheel for damage, particularly the leading edges of the blades where air enters the compressor.

The turbocharger is reassembled in the reverse order to that given above for the disassembly. However, it is necessary in the process to add or subtract shims to obtain the correct end clearance in the rotating assembly. Care must also be taken in replacing the exhaust inlet casing and the compressor inlet casing to not damage the compressor wheel or the turbine wheel and nozzle ring.

Most of the FM engines that are turbocharged have an adapter section in the exhaust piping just prior to the turbocharger exhaust inlet connection. This section contains a conically shaped screen like section to preclude engine parts from entering the turbocharger. The clearances between the end of the nozzle ring and the turbine blades are such that parts of piston rings that may have failed, for instance, will not pass through the turbine and may ‘machine’ the turbine blades. Therefore, the screen section is intended to trap these parts and prevent them from entering the turbocharger. There are small boxes attached to these transition sections in which this debris is collected. These should be inspected periodically to see that they are clear. If debris is found, the engine should be inspected to determine the source of the debris. The most likely source is pieces of broken piston rings and this section is often referred to as the ‘ring catcher’.

5.2 Scavenging Air Blower

Using the cutaway blower, the instructor will discuss its construction and operation. Its gear drive from the engine and mounting on the engine will be shown.

HANDS-ON SESSION 6

6.0 FUEL INJECTION PUMPS, FUEL INJECTION NOZZLES

Purpose

This session's purpose is to complement the classroom instruction of Chapter 4.

Learning Objectives

Upon completion of this lesson you will be able to understand:

- The disassembly/assembly and test of fuel injection pumps and how they operate.
- The disassembly/assembly of fuel injection nozzles and how they operate.

6.1 Injection Pumps and Nozzles

The students, with the assistance and directions of the instructor, will dissemble a PC engine injection pump. After disassembly, the pump parts will be examined and explained. This injection pump is similar to the OP engine injection pump, but much larger. The relationship of the injection pump to the cam shaft and tappet assembly will be explained and demonstrated.

6.2 Injection Nozzle Assemblies

The injection nozzle is a very important part of the engine. If the injection nozzle does not function properly, the fuel in not properly atomized into the cylinder and the fuel may not burn properly. This affects the operation of the engine by making exhaust temperatures higher than normal and fuel consumption higher than it ought to be.

The nozzle should open sharply when the fuel pressure reaches the point of opening the nozzle and spraying the fuel. The nozzle should also close sharply such that there is no dribbling or leaking from the nozzle once it closes. The nozzle should open at a specific pressure.

The purpose of this exercise is to disassemble several injection nozzles of various types, and to inspect the parts. The nozzles are then reassembled and tested to see that they operate properly. The testing process is generally referred in the industry as pop testing. Refer to injector nozzle illustrations Figure 3-39 and Figures 4-21 through 4-28.

At the instructor’s direction, disassemble the injection nozzles provided. Several students may be assigned to do so on several different nozzle types simultaneously. The instructor will direct which parts are to be inspected and how an inspection is carried out.

The students will then be instructed on how to reassemble the nozzles, generally in the reverse order to their disassembly. Some nozzle assemblies have copper gaskets which must be annealed before being installed into the nozzle assembly. Annealing is carried out by heating the gaskets to a cherry red color and then quenching it in water. The gasket must then be inspected to see that it was not damaged in the annealing process.

After the nozzles are reassembled, attach the nozzle assembly to a nozzle test stand and pump the hand pump to make the nozzle pop open. The nozzle should open at or slightly above a specified pressure and spray fuel in the form of a fine mist. When the pressure is relieved, the nozzle should not leak. Also, the nozzle should pop shut and not leak as the pressure is increased even though it has not yet popped.

CAUTION: Keep hands away from the nozzle tip when pop testing the nozzle. The fuel comes out of the nozzle at a high enough pressure to cause injury to the fingers or hand.