**PDHonline Course E494 (4 PDH)**

# An Introduction to Prime Movers for Auxiliary Power Systems

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*J. Paul Guyer, P.E., R.A.*

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**1. MECHANICAL ENERGY.** A prime mover is an engine that converts hydraulic, chemical, or thermal energy to mechanical energy with the output being either straight-line or rotary motion. Rotary mechanical energy is used to drive rotary generators to produce electrical energy. Over the last 125 years, the internal combustion engine, steam turbine and gas turbine have displaced the steam engine. Auxiliary electrical generators are today usually driven by either reciprocating engine or gas turbine. These are available in wide ranges of characteristics and power rating, have relatively high thermal efficiency and can be easily started and brought on line. In addition, their speed can be closely regulated to maintain alternating current system frequency.

**1.1 FUEL IS BURNED** directly in the internal combustion engine. The burning air/fuel mixture liberates energy which raises the temperature of the mixture and, in turn, causes a pressure increase. In the reciprocating or piston engine this occurs once for each power stroke. The pressure accelerates the piston and produces work by turning the crankshaft against the connected load.

**1.1.1 RECIPROCATING SPARK IGNITION (SI) ENGINES.** These engines operate on the Otto Cycle principle typical for all reciprocating SI engines. The events are:

- **INTAKE STROKE.** A combustible fuel/air mixture is drawn into the cylinder.
- **COMPRESSION STROKE.** The temperature and pressure of the mixture are raised.
- **POWER (EXPANSION) STROKE.** Ignition of the pressurized gases results in combustion, which drives the piston toward the bottom of the cylinder.
- **EXHAUST STROKE.** The burned gases are forced out of the cylinder.

**1.1.2 FOUR STROKES** of the piston per cycle are required (four-stroke cycle or four-cycle). One power stroke occurs in two revolutions of the crankshaft.

**1.1.3 THE OUTPUT OF AN ENGINE** can be increased with some loss in efficiency by using a two-stroke (two-cycle) Otto process. During the compression stroke, the fuel/air mixture is drawn into the cylinder. During the power stroke, the mixture in the cylinder is compressed. Near the end of the power stroke, burned gases are allowed to exhaust, and the pressurized new mixture is forced into the cylinder prior to the start of the next compression stroke.

**1.1.4 IN THE OTTO CYCLE**, the fuel/air mixture is compressed and ignited by a timed spark. The exact ratio of fuel to air is achieved by carburization of a volatile fuel. Fuel injection is also in use in the Otto cycle to achieve more precise fuel delivery to each cylinder.

**1.1.5 FOUR-CYCLE SI** gasoline engines are used as prime movers for smaller portable generator drives (see fig 3-l). The advantages are:

- Low initial cost.
- Light weight for given output.
- Simple maintenance.
- Easy cranking.
- Quick starting provided fuel is fresh.
- Low noise level.

**1.1.6 THE DISADVANTAGES** of using four-cycle SI gasoline engines are:

- Greater attendant safety hazards due to use of a volatile fuel.
- Greater specific fuel consumption than compression ignition (CI) engines.

**1.1.7 RECIPROCATING CI ENGINES.** These operate on the Diesel Cycle principle typical for all CI engines. The-events are:

- **INTAKE STROKE.** Air is drawn into the cylinder.

- **COMPRESSION STROKE.** Air is compressed, raising the pressure but ‘also raising the temperature of the air above the ignition temperature of the fuel to be injected.
- **POWER STROKE.** A metered amount of fuel at greater-than-cylinder-pressure is injected into the cylinder at a controlled rate. The fuel is atomized and combustion occurs, further increasing pressure, thus driving the piston which turns the crankshaft.
- **EXHAUST STROKE.** The burned gas is forced from the cylinder.

**1.1.8 AS WITH THE SI FOUR-CYCLE ENGINE**, the four cycles of the CI engine occur during two revolutions of the crankshaft, and one power stroke occurs in every two revolutions.

**1.1.9 THE CI OR DIESEL ENGINE** may also use two cycle operation with increased output but at lower engine efficiency.

**1.1.10 IN THE DIESEL CYCLE**, only air is compressed and ignition of the fuel is due to the high temperature of the air. The CI engine must be more stoutly constructed than the SI engine because of the higher pressures. The CI engine requires highpressure fuel injection.

**1.2 GAS TURBINE ENGINE.** The fuel and air burn in a combustion chamber in the gas turbine engine. The resulting high-pressure gases are directed through nozzles toward the turbine blades and produce work by turning the turbine shaft. This is a continuous process in the continuous-combustion or constant pressure gas turbine.

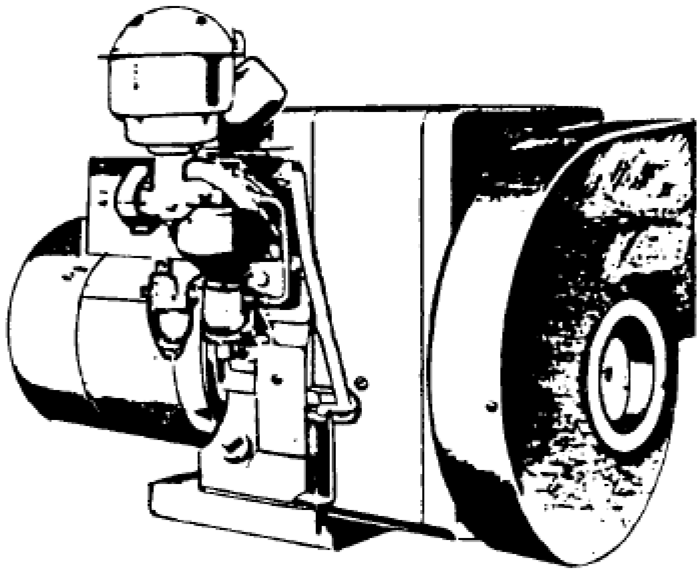


Figure 3-1

Typical gasoline powered emergency generator set, air cooled

**1.2.1 GAS TURBINES** operate on the Brayton Cycle principle. While a number of configurations are used for aircraft propulsion (turbofan, turboprop, etc.), the one used as a prime mover for auxiliaries is generally the continuous combustion gas turbine. In this process, air is compressed by an axial flow compressor. A portion of the compressed air is mixed with fuel and ignited in a combustion chamber. The balance of the compressed air passes around the chamber to absorb heat, and then it is merged with the burned products of combustion. The pressurized mixture, usually at 1000°F or higher, flows into a reaction turbine.

**1.2.2 THE TURBINE DRIVES THE COMPRESSOR** and also produces work by driving the generator. A portion of the exhaust gas may be recirculated and it is possible to recover heat energy from the waste exhaust. The compressor uses a relatively large portion of the thermal energy produced by the combustion. The engine efficiency is highly dependent on the efficiencies of the compressor and turbine.

**1.2.3 THE ADVANTAGES** of using a gas turbine are:

- Proven dependability for sustained operation at rated load.
- Can use a variety of liquid and gaseous fuels.
- Low vibration level.
- High efficiency up to rated load.

**1.2.4 THE DISADVANTAGES** of using a gas turbine are:

- Initial cost is high.
- Fuel and air filtering are required to avoid erosion of nozzles and blades.
- Fine tolerance speed reducer between turbine and generator is required and must be kept in alignment.
- Specialized maintenance, training, tools and procedures are required.
- Considerable energy is required to spin for start.
- High frequency noise level.
- Exhaust volume is considerable.
- A large portion of the fuel heat input is used by the compressor.
- A long bedplate is required.
- Maximum load is sharply defined.
- Efficiency is lower than reciprocating engines.

**1.3 ROTARY SPARK IGNITION ENGINES.** These engines are typified by the Wankel-type engine operating on the Otto principle. Each of the four cycles occurs in a specific sector of an annular space around the axis of the shaft. The piston travels this annular chamber and rotates the shaft. The power stroke occurs once in every shaft revolution, dependent on the design of the engine. This engine can produce a large amount of power for a given size. The high rpm, low efficiency, friction and sealing problems, and unfavorable reliability of this engine make it unsatisfactory as a prime mover for auxiliary generators. These faults may be corrected as the development continues.

**2. DIESEL ENGINES.** Diesel engines for stationary generating units are sized from 7.5 kW to approximately 1500 kW and diesel engines for portable generating units are sized from 7.5 kW to approximately 750 kW. See figures 3-2 through 3-4. Efficiency, weight per horsepower, and engine cost relationships are relatively constant over a wide range of sizes. Smaller engines, which operate in the high-speed range (1200 and 1800 rpm), are used for portable units because of their lighter weight and lower cost. Low and medium-speed (200 and 900 rpm) engines are preferred for stationary units since their greater weight is not a disadvantage, and lower maintenance cost and longer life offset the higher initial cost.

**2.1 THE ADVANTAGES** of diesel engines include:

- Proven dependability for sustained operation at rated load.
- Efficiency.
- Adaptability for wide range of liquid fuels.
- Controlled fuel injection.

**2.2 THE DISADVANTAGES** include:

- High initial cost.
- High weight per given output.
- High noise level.
- Specialized maintenance.
- Fuel injection system has fine mechanical tolerances and requires precise adjustment.
- Difficult cranking.
- Cold starting requiring auxiliary ignition aids.
- Vibration.

**3. TYPES OF DIESEL ENGINES.** Various configurations of single and multiple diesel engines, either two-cycle or four-cycle are used to drive auxiliary generators. Multi-cylinder engines of either type can be of "V" or in-line configurations.

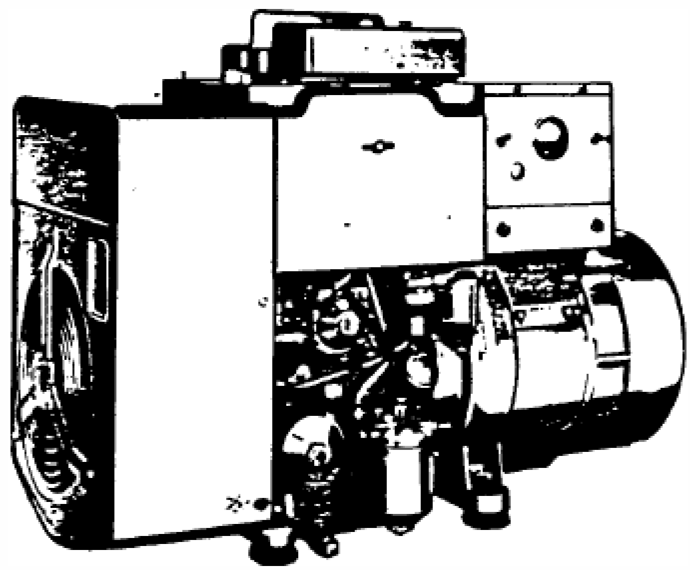


Figure 3-2

Typical small stationary diesel generator unit, air cooled

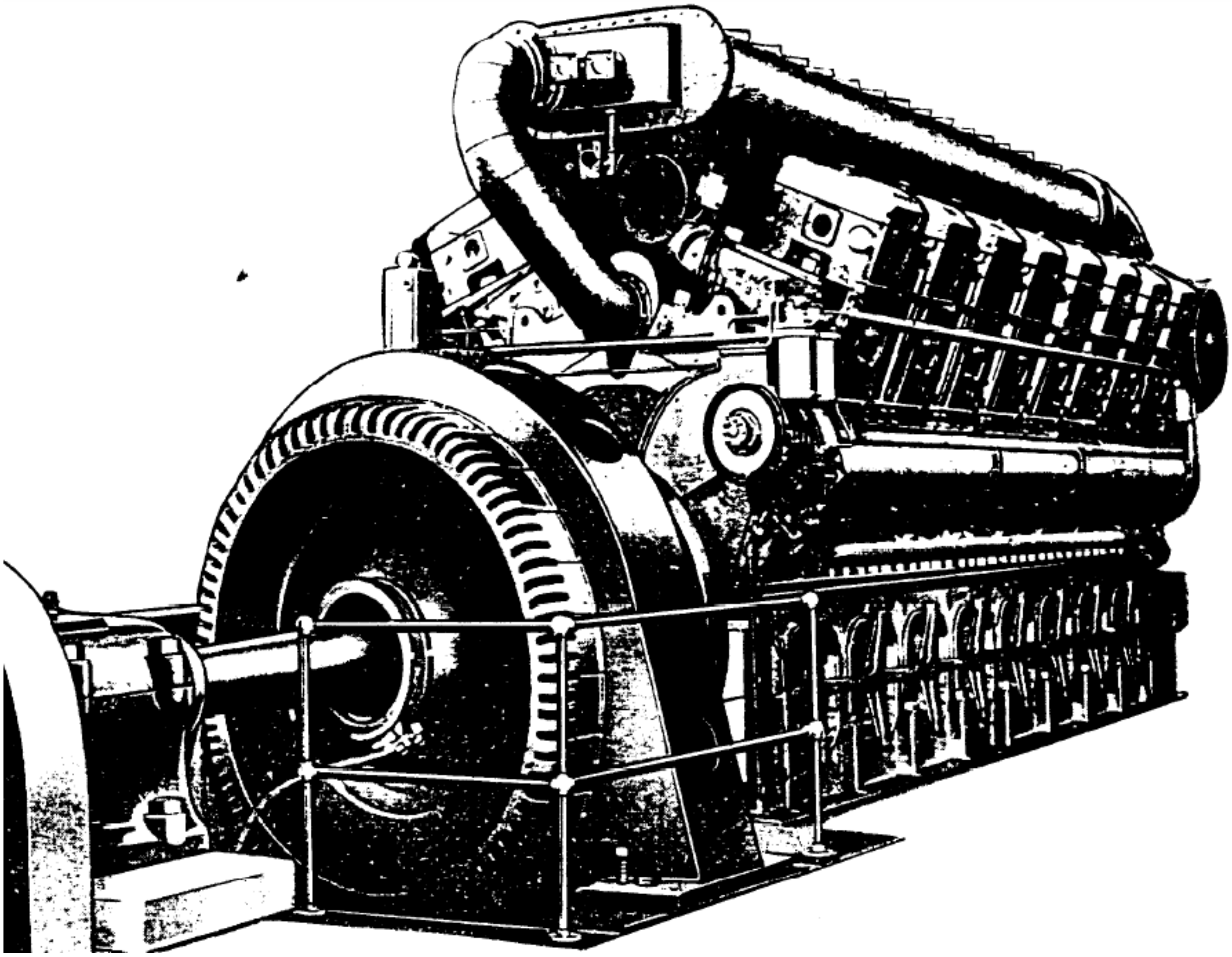


Figure 3-3

Typical large stationary diesel generator unit.

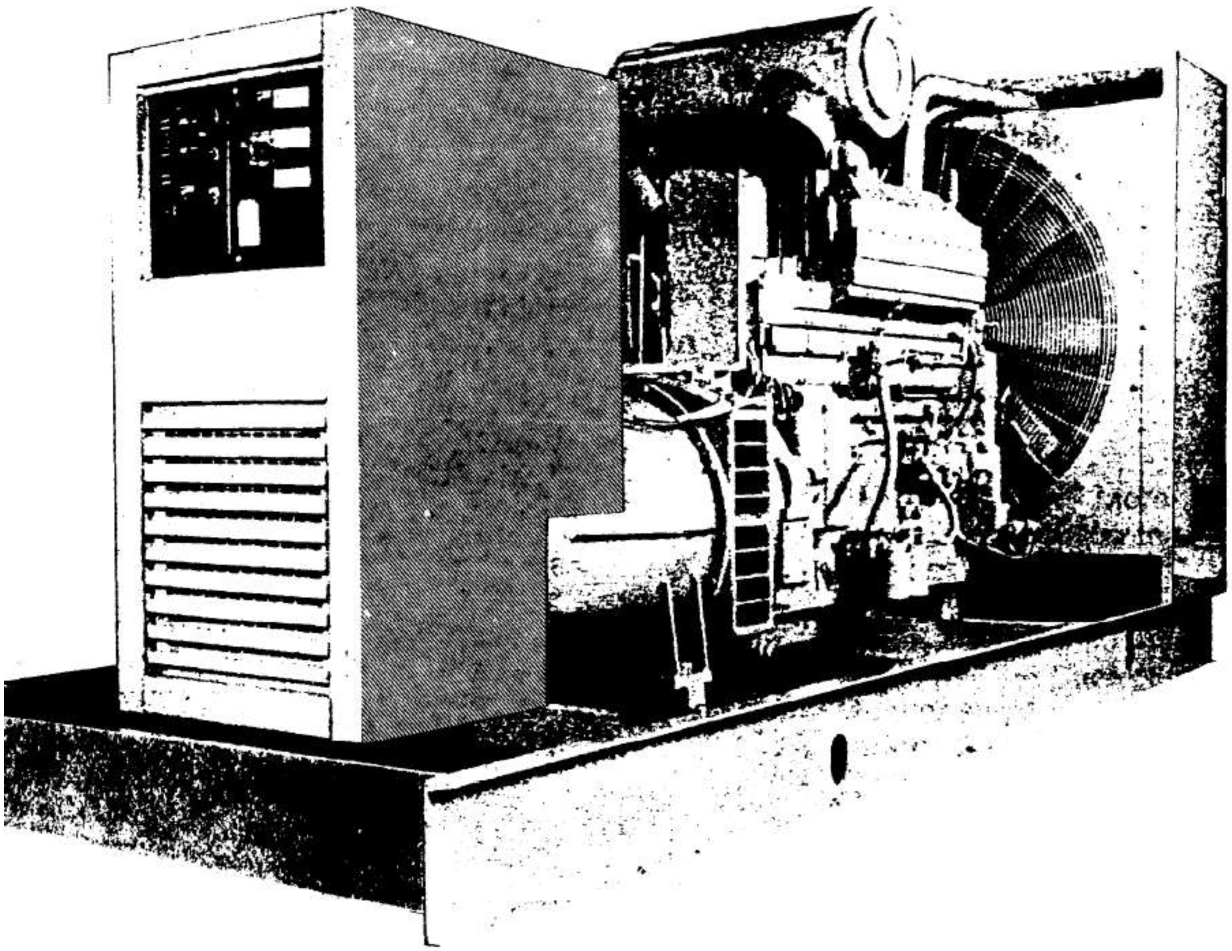


Figure 3-4

Typical diesel power plant on transportable frame base.

The “V” configuration is favored when there is a lack of space because “V” engines are shorter and more compact than in-line engines. Most engines in use are liquid-cooled. Air cooling is sometimes used with single-cylinder and other small engines (driving generators with up to 10 kW output). Air-cooled engines usually reach operating temperature quickly but are relatively noisy during operation.

**3.1 TWO CYCLE.** The series of events that take place in a two-cycle diesel engine are: compression, combustion, expansion, exhaust, scavenging, and air intake. Two strokes of the piston during one revolution of the crankshaft complete the cycle.

**3.1.1 COMPRESSION.** The cycle begins with the piston in its bottom dead center (BDC) position. The exhaust valve is open permitting burned gases to escape the cylinder, and the scavenging air port is uncovered, permitting new air to sweep into the cylinder. With new air in the cylinder, the piston moves upward. The piston first covers the exhaust port (or the exhaust valve closes), then the scavenging air port is closed. The piston now compresses the air to heat it to a temperature required for ignition as the piston nears top dead center (TDC). As the piston nears TDC, a metered amount of fuel is injected at a certain rate. Injection atomizes the fuel, which is ignited by the high temperature, and combustion starts. Combustion causes the temperature and pressure to rise further.

**3.1.2 POWER:** As the piston reaches and passes TDC, the pressure of the hot gas forces and accelerates the piston downward. This turns the crankshaft against the load connected to the shaft. The fuel/air mixture continues to burn. As the piston passes eighty percent (80%) to eighty-five percent (85%) of the stroke travel towards BDC, it uncovers the exhaust port (or the exhaust valve is opened). This allows exhaust gas to escape from the cylinder. As the piston continues downward, it uncovers the scavenging air port, allowing scavenging air (fresh air at 3 pounds per square inch (psi) to 6 psi) to sweep the cylinder, further purging the exhaust gas and providing a fresh clean charge for the next cycle. The piston reaches and passes through BDC. The compression stroke then begins again.

**3.2 FOUR-CYCLE.** The series of events taking place in a four-cycle engine are: inlet stroke, compression stroke, expansion or power stroke, and exhaust stroke. Four strokes (two revolutions of the crankshaft) are necessary to complete the cycle.

**3.2.1 INLET STROKE.** As the piston starts downward from TDC, the inlet (intake) valve opens and allows the piston to suck a charge of fresh air into the cylinder. This air may be supplied at a pressure higher than atmospheric air by a supercharger.

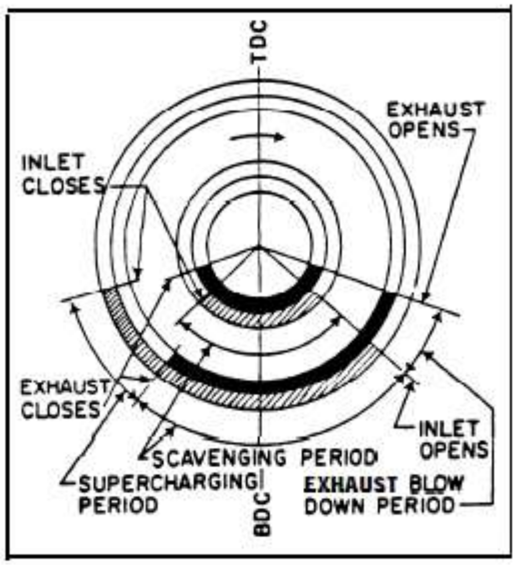
**3.2.2 COMPRESSION STROKE.** As the piston nears BDC, the air inlet valve closes, sealing the cylinder. Energy supplied by the crankshaft from a flywheel, or power from other cylinders, forces the piston upward toward TDC, rapidly compressing the air and increasing the temperature and pressure within the cylinder.

**3.2.3 POWER STROKE.** As the piston approaches TDC, an amount of fuel (modulated by the governor) is injected (sprayed and atomized) into the cylinder which is ignited by the high temperature, and combustion starts. Combustion, at a controlled rate, further increases the temperature and pressure to accelerate the piston toward BDC. The expansion of the hot gases forces the piston down and turns the crank against the load. Engine efficiency depends on the fuel charge being completely burned during the power stroke.

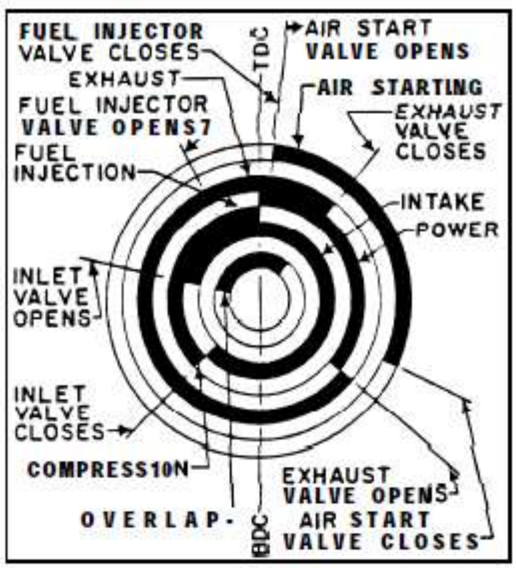
**3.2.4 EXHAUST STROKE.** As the piston passes through BDC at the end of the power stroke, the exhaust valve opens. The piston, using stored energy from the flywheel or from the power stroke of another cylinder, forces the burned gases from the cylinder through the exhaust port. As the piston approaches TDC, the exhaust valve is closed and the air intake valve opens to begin another cycle.

**3.3 ENGINE TIMING.** Engine timing is critical. Intake and exhaust valves have to open and close to allow the greatest amount of work to be extracted from combustion. They must also be open long enough to allow fresh air to flow into and exhaust gas to flow out of the cylinder. Fuel must be injected at proper rates during certain periods of time to get smooth pressure rise and complete combustion. Timing for two-stroke cycle and four-stroke cycle engines differs (refer to the timing diagrams in fig 3-5). Diagram A illustrates two forms of the two-stroke cycle engine. The inner portion covers the typical crankcase scavenging type with uncontrolled fixed ports. The outer portion covers a port control (uniflow) system. Diagram B illustrates timing for a fourstroke cycle engine.




A.




B.

Figure 3-5. Timing diagrams

A: for a two stroke cycle,

B: for a four stroke cycle.

**3.4 ADVANTAGES.** Advantages of diesel power for generating units include the ability: to utilize specific liquid or gaseous fuel other than highly volatile refined ones (gasoline, benzene, etc.); to meet load by varying the amount of fuel injected; to utilize a relatively slow design speed; and, to operate without external furnaces, boilers or gas generators.

**3.5 DISADVANTAGES.** Major disadvantages include: a need to reduce cranking power by use of compression relief during start and a powerful auxiliary starting engine or starting motor and battery bank; high-pressure, close-tolerance fuel injection systems capable of being finely adjusted and modulated for speed/load control; weight; and, noise.

**4. DIESEL FUEL SYSTEM.** A typical diesel engine fuel system is shown in figure 3-6. Information related to cooling, lubrication, and starting systems is also shown. Functional requirements of a diesel engine fuel system include fuel injection, injection timing, and fuel pressurization.

**4.1 FUEL INJECTION SYSTEM.** This system measures and meters fuel supplied to each cylinder of the engine. Either inlet metering or outlet metering is used. In inlet metering, fuel is measured within the injector pump or injector. In outlet metering, fuel is measured as it leaves the pumping element. Instantaneous rate during injection must deliver fuel to attain correct propagation of the flame front and resulting pressure rise.

**4.2 TIMING.** Fuel injection timing is critical. The duration of fuel injection and the amount of fuel injected vary during starting and partial, full, or overload conditions, as well as with speed. The best engine start occurs when fuel is injected at (or just before) TDC of piston travel because air in the combustion chamber is hottest at that instant. During engine operation, the injection timing may need to be advanced to compensate for injection lag. Many modern injection systems have an automatic injection timing device that changes timing to match changes in engine speed.

**4.3 FUEL PRESSURIZATION.** Fuel must be pressurized to open the injector nozzle because the nozzle (or injector tip) contains a spring-loaded check valve. The injection pressure must be greater than the compression pressure within the compression chamber or cylinder. Between 1500 psi and 4000 psi pressure is required for injection and proper fuel atomization. Specific information is provided in the engine manufacturer's literature.

**4.4 FUEL CONTAMINATION.** Fuel injection equipment is manufactured to precision accuracy and must be very carefully handled. A small amount of abrasive material can seriously damage moving parts. Contaminated fuel is a major vehicle by which dirt and water enter the system. Fuel must be filtered before use.

**4.5 STARTING FUELS.** Diesel engines used for auxiliary generators usually use distillate fuel for quicker starting. These fuels are light oils that are similar to kerosene. Various additives are frequently used with fuel such as cetane improvers which delay ignition for smoother engine operation, corrosion inhibitors, and dispersants.

**4.6 INJECTION SYSTEMS.** Diesel engine manufacturers usually use one of the following types of mechanical fuel injection systems: unit injection, common rail injection, or in-line pump and injection nozzle. A limited number of diesel engines currently in use employ a common rail injection system. Electronic fuel injection has been developed for use in modern diesel engines refer to paragraph 3-4b(4). Unit injector, common rail injector, and in-line pump and injection nozzle systems are described in tables 3-1 through 3-3. Injection of fuel in any system must start and end quickly. Any delay in beginning injection changes the injection timing and causes hard starting and rough operation of the engine. Delay in ending injection is indicated by heavy smoke exhaust and loud, uneven exhaust sounds. The end of injection (full shutoff) should be total with no dribble or secondary injections. Some injection systems include a delivery or retraction valve for fuel shutoff. In other systems, camshafts have cam lobes designed with a sharp drop to assure rapid fuel shutoff.

**4.6.1 COMMON RAIL INJECTION.** The common rail injection system is an older system where fuel is supplied to a common rail or manifold. A high-pressure pump maintains a constant pressure in the rail from which individual fuel lines connect to the injection or spray nozzle at each cylinder. Fuel is drawn from the supply tank by the low-pressure pump and passed through a filter to the suction side of the high-pressure pump. The high-pressure pump raises the fuel to the engine manufacturer's specified operating pressure. Constant pressure is maintained in the system by the high pressure pump and related relief valve. If pressure is greater than the relief valve setting, the valve opens and permits some of the fuel to flow back (bypass) into the tank. Check valves in the injection nozzle prevent the return of fuel oil to the injection system by cylinder compression pressure.

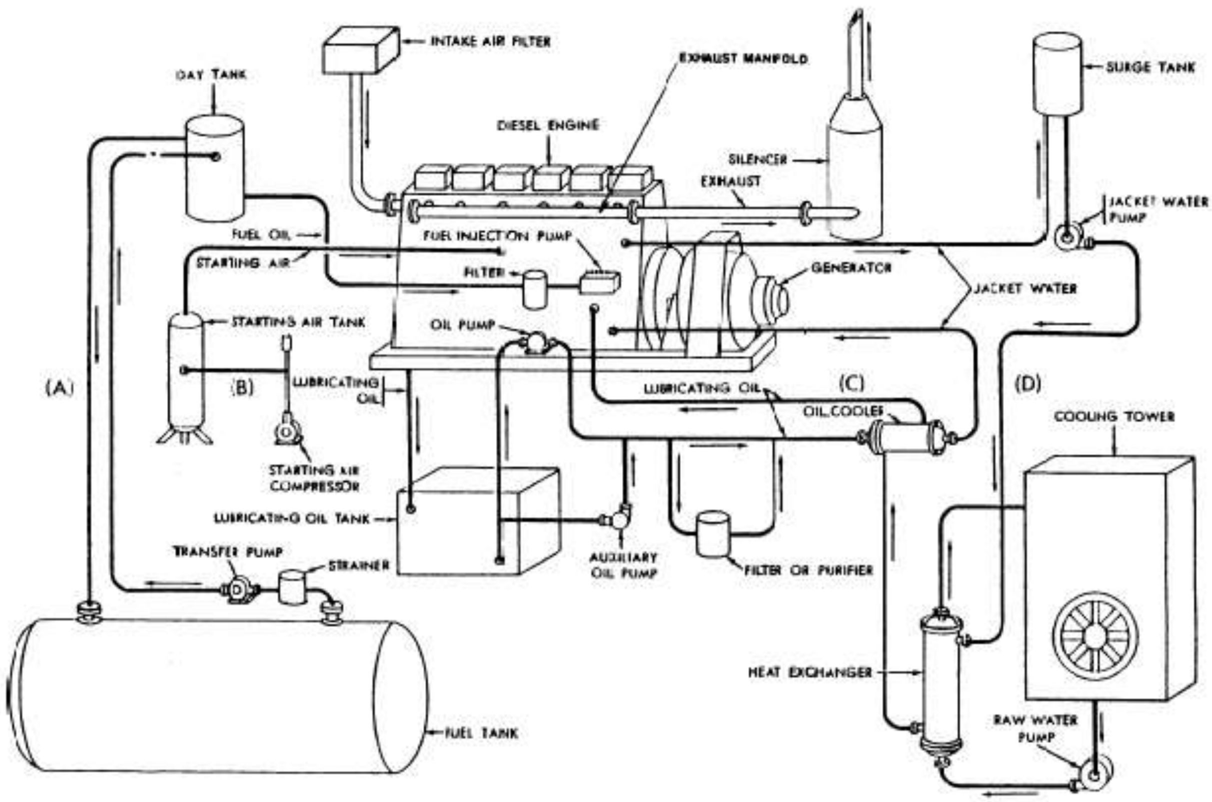



Figure 3-6.

Diagram of typical fuel, cooling, lubrication, and starting systems.

| Component | Purpose |
|---|---|
| Gear pump | Low pressure pump; delivers fuel from tank to injector: fuel also lubricates the pump. |
| Injector | Meters, times, and pressurizes fuel: camshaft-operated by pushrod and rocker arm; one injector for each cylinder. |
| Filters | Protect machined components from dirt and water in fuel. |
| Governor | Controls engine speed. Varies position of the injector plunger to vary amount of fuel injected. |

Table 3-I

Unit injector system

| Component | Purpose |
|---|---|
| Low and high-pressure pump | Low-pressure pump delivers fuel from tank to high-pressure pump; high-pressure pump delivers fuel to injectors at the desired operating pressure: fuel lubricates governor and pumps. |
| Governor | Flyweight-type; controls maximum fuel pressure; prevents engine overfueling; controls engine idle and prevents overspeeding by controlling fuel supply: contained within main pump housing. |
| Throttle | Controlled by the operator; regulates fuel flow and pressure to injectors. |
| Injector | Meters, times and pressurizes fuel; camshaft-operated by pushrod and rocker arm: one injector for each cylinder. |
| Filters | Protect machined components from dirt and water in fuel. |

Table 3-2

Common rail injector system

| Component | Purpose |
|---|---|
| Injection pump | Meters, times, pressurizes and controls fuel delivered to the injection nozzles; consists of single pumping element for each cylinder; titted into a common housing; operated by rocker arm or directly from the camshaft. |
| Governor | Usually the flyweight-type: may be mounted on main injection pump housing; controls fuel delivery: variable-speed or limiting-speed type is used. |
| Fuel lines | High-pressure type; transports fuel from pump to injection nozzles. |
| Injection nozzle | Spring-loaded; hydraulically operated valve that is inserted in the combustion chamber: one nozzle for each cylinder. |
| Filters | Protect machined components from dirt and water in fuel. |

Table 3-3

In-line pumps and injection nozzle system.

**4.6.2 UNIT INJECTION.** This system consists of an integral fuel-injector pump and injector unit. A complete unit is required for each cylinder. Fuel oil is supplied to the cylinders by individual pumps operated from cams located on a camshaft or on an auxiliary drive. The pumps operate independently of each other. Fuel from the supply tank is passed through a filter to the injector pump supply pipe. The injector pump receives the fuel which is then injected into the cylinders in proper quantity and at a prearranged time.

**4.6.3 ELECTRONIC FUEL INJECTION.** The electronic fuel injection system is an advanced design for modern diesel engines, intended to produce improved starting and operating characteristics. Several systems have been developed, mainly for smaller and intermediate-sized engines. Similarities to mechanical injection systems include the following: a fuel pump (or pumps), a governor or speed regulator, filters, and fuel injectors. The major difference between mechanical and electronic systems is the computer which replaces the mechanical components (cams and pushrods) used to control fuel injection. The computer processes data inputs (such as engine speed and load, desired speed or governor setting, engine temperature, and generator load). Computer output is precisely timed electrical signals (or pulses) that open or close the fuel injectors for optimum engine performance. Adjustment of injection timing is seldom required after the initial setup. Refer to the engine manufacturer's literature for maintenance of injectors, pumps, and other fuel system components.

**4.7 THE MAIN COMPONENTS OF THE FUEL SYSTEM.** Fuel supply source, transfer pump, day tank, fuel injection pump, fuel injection nozzles, and filters and strainers. These components are matched by the engine manufacturer for optimum performance and warranty protection.

**4.7.1 THE FUEL SUPPLY SOURCE** is one or more storage tanks. Each tank must have drain valves for removal of bottom water. Additionally, the fuel system should include a day tank and a transfer pump.

**4.7.2 THE FOLLOWING PARAGRAPHS** cover the fuel injection pump, fuel injection nozzles, and filters and strainers.

**4.7.3 A FUEL INJECTION PUMP** accomplishes the functions described. Additional details are provided in the following paragraphs.

- The fuel injection pump must perform two functions: first, deliver a charge of fuel to the engine cylinder at the proper time in the engine operating cycle, usually when the piston has almost reached the end of the compression stroke; and second, measure the oil charge delivered to the injector so the amount of fuel is sufficient to develop the power needed to overcome the resistance at the crankshaft.

- The fuel injection pump consists of a barrel and a reciprocating plunger. The reciprocating plunger takes a charge of fuel into the barrel and delivers it to the fuel-injecting device at the engine cylinder.

**4.7.4 FUEL INJECTION NOZZLES** for mechanical injection systems are usually of the spring-loaded, needle-valve type. These nozzles can be adjusted to open at the predetermined pressure. Consult the manufacturer's specifications before adjusting fuel injection valves. The nozzle components are assembled carefully at the factory and must never be intermixed. Most manufacturers use an individual pump for each cylinder (pump injection system) and provide each cylinder with a spring-loaded spray valve. The spring keeps the needle from lifting until the pump has delivered oil at a pressure greater than the spring loading. As soon as the pressure lifts the needle, oil starts to spray into the engine cylinder through an opening in the valve body.

**4.7.5 DIESEL FUEL SUPPLIERS** try to provide clean fuel. However, contaminants (water, sand, lint, dirt, etc.) are frequently found even in the best grades. If foreign material enters the fuel system, it will clog the nozzles and cause excessive wear of fuel pumps and injection valves.

**4.7.6 SULPHUR**, frequently found in fuel oil, is very undesirable. When sulfur is burned (during combustion), sulfur dioxide and sulfur trioxide form. Both substances will combine with water condensates to form sulfuric acid. The maximum amount of sulfur acceptable in fuel oil must not exceed one percent. The engine manufacturer's recommendation should be used if acceptable sulfur in fuel oil requirements are more restrictive. Strainers and filters capable of removing fine particles are placed in the fuel line between supply tank and engine, or between engine transfer pump and injection pump, or sometimes at both places. The basic rule for placement of strainers and filters is strainers before pumps, filters after pumps. A filter should be placed in the storage tank fill line. This prevents accumulation of foreign material in the storage tank. Strainers protect the transfer pumps. A strainer should also be placed ahead of each fuel flow meter. Always locate filters and strainers where they are easily accessible for cleaning or replacement. Duplex filters should be provided for engines that run continuously so that filter elements can be cleaned while the engine is running without interrupting its fuel supply. Provide space under the edge of disk filters for a receptacle to receive material drained from the bottom of the filter when it is cleaned. If the filter or strainer has an element that can be renewed or cleaned, space must be allowed to permit its easy removal. Follow the manufacturer's recommendations on frequency of cleaning and replacing filter elements. Adjust the frequency to meet unusual local operating conditions. Generally, all metal-edge and wire mesh devices are called strainers, and all replaceable absorbent cartridge devices are called filters. Fuel filters approved for military use consist of replaceable elements mounted in a suitable housing. Simplex and duplex type fuel filters are available. Fuel strainers and filters must not contain pressure relief or bypass valves. Such valves provide a means for the fuel to bypass the strainer or filter, thereby permitting the fuel-injection equipment to be damaged by contaminated fuel. Filter capacity is generally described in terms of pressure drop between the input and output sides of the filter. However, fuel oil filters must be large enough to take the full flow of the fuel oil pumps with a pressure drop across the filter not to exceed the engine manufacturer's specifications. Fuel filter elements should be changed whenever the pressure drop across the filter nears or reaches a specified value. Refer to manufacturer's instructions for information on the replacement of filter elements. Filter capacity at a given pressure drop is influenced by the viscosity of the fuel. The filter should have ample capacity to handle fuel demand of the engine at full load. The larger the filter, the less frequently it will have to be cleaned and the better the filtering performance will be.

**5. DIESEL COOLING SYSTEM.** Diesel engines are designed to be either air cooled or liquid cooled. Cooling is used to prevent the cylinder walls, the head, the exhaust manifold, and the lube oil from overheating.

**5.1 AN AIR-COOLED SYSTEM** depends on an engine driven fan to blow ambient air over the fluted or finned surfaces of the cylinder head and through a radiator type oil cooler, and over the exhaust manifold. The exterior surfaces must be kept free of dirt or corrosion. The oil must be kept free of sludge to secure adequate cooling. Air cooling is seldom used on engines over 5 HP or on multicylinder engines.

**5.2 THE LIQUID-COOLED ENGINE** uses a treated coolant forced to circulate through passages in and around the cylinder, head, exhaust manifold and a lube oil heat exchanger. The hot coolant is passed through the tubes of an air-cooled radiator, through the tubes of an evaporative heat exchanger, or through a shell and tube heat exchanger. A typical liquid system is shown in figure 3-7.

**5.2.1 TWO BASIC TYPES** of liquid-cooling systems are attached and remote.

- **ATTACHED.** All components are mounted at the engine. It is used with smaller and/or portable engine generator sets and usually consists of an engine-driven pump circulating treated coolant in a closed circuit through a radiator (engine-driven fan) or a water-cooled heat exchanger.

- **REMOTE.** Primary coolant in a closed circuit is piped to a heat exchanger system not mounted with the engine. Pumps and controls may also be remote. It is used for larger engines where size and complexity of heat dissipation systems are significant. It is also used to physically separate the liquid processing from the electrical generation and control spaces.

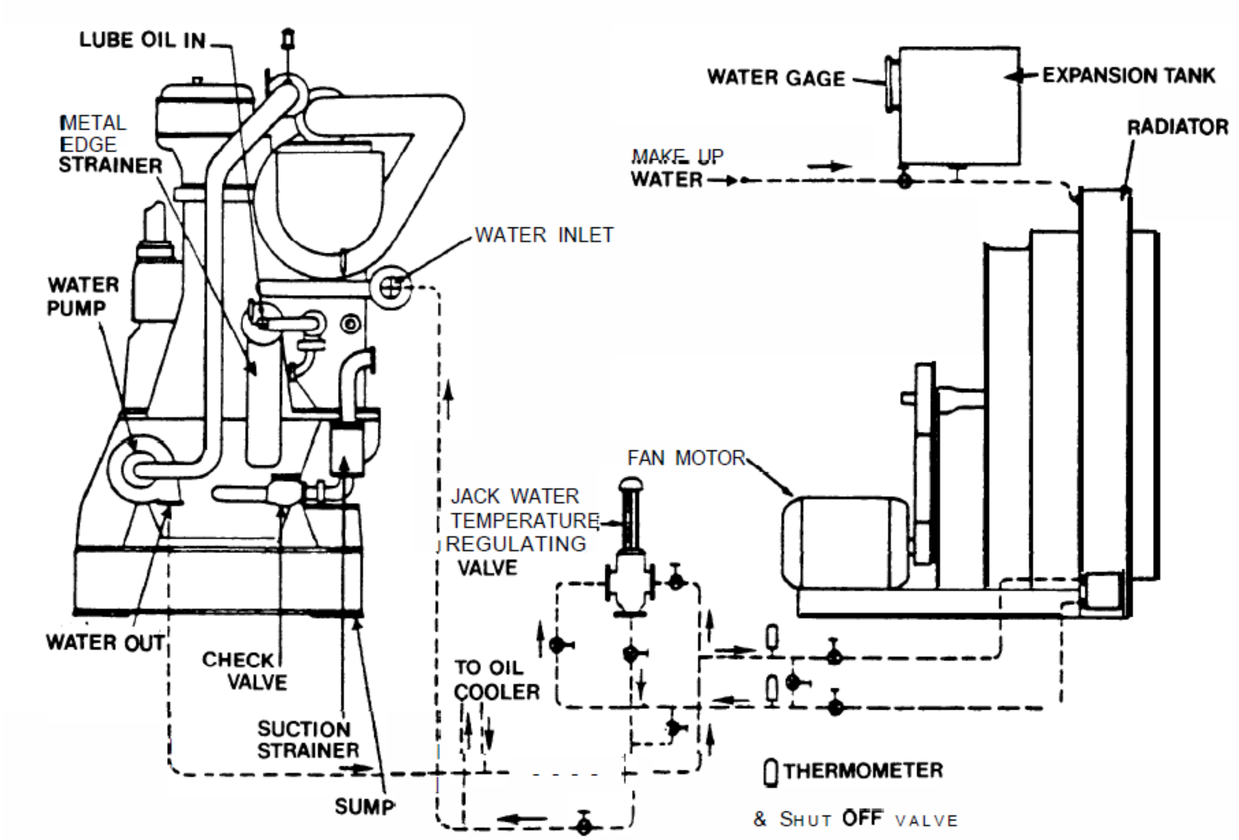



Figure 3-7

Diesel Engine Liquid Cooling System

**5.3 SYSTEM DESCRIPTION AND OPERATION.** Successful operation of the engine depends upon the removal of excess heat from lubricating oil, after cooler, and the engine components (cylinders, pistons, and valves) to keep the engine temperature within the limits specified by the manufacturer. The kW rating of the associated electric generator may require derating when any temperature at the operating engine exceeds the manufacturer's limits. Table 3-4 describes the various elements of the cooling system.

**5.3.1 OVERHEATING OF THE ENGINE** reduces the effectiveness of engine lubricants, accelerates engine wear, and causes engine breakdown. Cooling prevents excessive stresses in or between engine parts caused by unequal temperature within the engine. Also, cooling prevents loss of strength caused by overheating of the engine's structural metal.

**5.3.2 THE ENGINE AND ITS COMPONENTS** are designed to withstand the mechanical and thermal stresses resulting from operating within certain parameters. The design also allows for the effects of temperature on the strength, resistance to fatigue and wear, the stresses induced by expansion and contraction, and allowance for wear and corrosion, etc.

- Each component subject to heat is designed to operate within stated temperature limits. Unsatisfactory operation, decreased life, damage or failure will result if the engine operates outside of these limits. Lubricants will lose their necessary properties, clearances between parts will become too great or too little, and combustion of fuel will not be proper. Fuel, air, exhaust and coolant passages may be fouled, melted, or chemically attacked, or misalignment and excessive vibrations may result.

- Hot spots, cold spots, general overheating and general overcooling can each cause problems. Approximately one-third of the energy consumed by an engine is removed by the cooling system.

**5.3.3 AN ENGINE USED FOR** auxiliary generator service will be one of proven capability and reliability when operated within the limits specified by the manufacturer. A particular engine will require stated rate of coolant flow at certain inlet and outlet temperatures under various rates of fuel energy consumption and mechanical energy output.

| Component | Purpose |
|---|---|
| Coolant | The liquid, usually treated water, used to remove excess heat from the engine. May be primary, secondary, etc. |
| Coolant jackets or passages | Spaces surrounding block, cylinders, and heads, through which primary coolant is circulated under pressure to cool the engine components. |
| Coolant pumps | Water or primary (secondary, other) pump to circulate coolant (water) through engine passages to heat exchangers. |
| Thermostat | Regulates coolant flow to maintain engine temperature between specified limits. |
| Fan | Provides air movement to cool air-cooled engine or the radiator of a liquid-cooled engine to cool the coolant for recirculation. |
| Shutters | Blades used to vary air flow across a radiator to regulate rate of heat removal from coolant. Would be closed when coolant is below normal temperature and open when coolant is warm. May be thermostatically controlled. |
| Heat exchanger | A device to exchange heat from one medium to another. Usually a shell and tube-type exchanger. |
| Coolant tower | A structure in which hot coolant is sprayed or falls through air currents. As coolant evaporates heat is given up by the remaining liquid coolant. |
| Evaporative cooler | A device to remove heat from medium by evaporation of that medium in air (open circuit). May also be by non-contact heat exchanger from one medium to an evaporating second. Applicable where ambient temperature and relative humidity are below certain values. |
| Treated coolant | Coolant fluid, usually filtered water with additives to prevent freezing and to inhibit scale formation and corrosion. Required for primary coolant circuit. May not be required for secondary or other circuits. |
| Secondary system | Describes the components of a second system used to extract heat from the primary heat exchanger. Used where waste heat may be used for building heating, etc. |
| Tertiary system | Describes components of a possible third system to extract heat from a secondary system. |
| Closed system | Coolant does not come in contact with air or other fluids. |

Table 3-4

Typical cooling system components

The coolant must not contain any suspended solids that could settle and impede heat transfer or coolant flow. The coolant should be free of entrained or dissolved air or other gases which could cause corrosion and decrease heat transfer. The coolant should not contain dissolved salts' that could precipitate or form an insulating scale coating which also decreases heat transfer. It should have good heat capacity and contain an antifreeze, anticorrosion compound, and cleaning agent to keep coolant passages in good condition. The coolant should neither corrode nor attack any metals or organic materials of the coolant system. It should not be hazardous.

**5.3.4 IN RARE CASES**, the engine may be cooled using clean water in a once-through system. Cool water is pumped through the coolant passages, and the hot water leaving the engine is discarded. This has many disadvantages and will not be further discussed.

- Smaller engines may have a single cooant circuit (loop) through which coolant, passes and is returned to the engine.

- Larger engines may require the use of additional loops. In these, the engine coolant is in a primary loop. It is cooled by the medium circulating in a secondary loop and the secondary coolant may be cooled by another medium in a tertiary loop. No cooling medium mixes with another medium in these "non-contact" systems.

- An example of a three-loop system is treated engine coolant in the primary loop passing through a heat exchanger cooled by freshwater in a secondary loop. The "hot" freshwater may be used for building heating or may be passed through another heat exchanger cooled by brackish or saltwater in the tertiary circuit on a once-through basis. The purpose of this arrangement is to keep the seawater at low temperatures so that salts do not form scale. Leakage of seawater into the freshwater circuit is prevented by having the freshwater at higher pressure than the seawater. The freshwater circuit may operate at higher temperature and recover significant usable heat otherwise wasted.

- Contamination of engine coolant is prevented by being at a higher pressure than the freshwater. The additives used in the engine coolant are a cost. Very little coolant is lost when the coolant circuit is sealed. Heat capacity and temperature may be elevated by using a sealed, pressurized coolant loop. Coolant must be periodically tested to make sure correct amounts of active additives are present.

- At the engine the coolant cools the lubricating oil, then the lower temperature areas, and finally the hotter sections.

- In the crankcase the oil cools the crankshaft assembly. Sprayed or splashed oil cools the underside of the piston. Oil circulated to the camshaft, rocker arms, and valve guides picks up heat and drains into the sump. The oil pump forces the hot lube oil through the oil filter and through the oil cooler to the pressure-oiled points. The oil must not become so hot that it loses its lubricating properties or breaks down.

- Coolant leaving the oil cooler flows to the cylinder water jackets, inlet ports and valves, injectors, exhaust ports and valves, intercooler or supercharger, turboblower, exhaust manifold jacket, and finally to the heat exchanger where it is recirculated to the engine.

**5.3.5 NON-CONTACT HEAT EXCHANGERS** are used to add or remove heat from one medium to another without intermixing. A radiator or fin-fan cooler uses an airflow to remove and dissipate the heat. In a heat exchanger, one medium flows through tubes and the second medium flows around the tubes. Generally, the medium having a higher tendency to foul the exchanger surfaces is inside the tubes to allow easier cleaning. The tubes may form part of a sealed system. The tube bundle may be in an open tank or in a shell. The shell, enclosing the second medium, may be part of another sealed system.

**5.3.6 COOLING TOWERS** and evaporative coolers are both used to dissipate waste heat to the atmosphere. They may be used where ambient air is sufficiently cool and dry (low relative humidity) to absorb water vapor. As water is sprayed or divided into many small streams, some will evaporate to the passing air. The heat required to evaporate the water is approximately 1050 Btu/lb and is extracted from the unevaporated water. Additionally, the air which is now moist may be warmed by the water (if the water was originally warmer than the air), thus removing more heat from the water. In a cooling tower, the fluid to be cooled is exposed to the air. Approximately eighty percent (80%) of the heat removed is due to evaporation. The water leaving the tower or cooler is usually five degrees Fahrenheit (5°F) higher than the entering air. Towers may use atmospheric draft or fans to move the air. Makeup water is required to replace that lost by evaporation or entrained spray. Water treatment and blowdown are necessary because salts are concentrated by the evaporation. Dust, etc., in the air will contaminate the exposed water. In an evaporative cooler, the coolant passes through tubes. The tube bundle lies inside a cooling tower. The cooling tower spray and air movement cool the tubes but do not mix with the coolant.

**5.3.7 FLOW RATES OF FLUID**, fan speed, flow bypass, etc. are controlled to maintain proper conditions. A properly monitored, real-time, automatic control system is preferred over a manually-operated system, especially where some parts of the engine auxiliaries are remote or not in direct observation of operating personnel. Automatic data logging is of real value for determining trends and for troubleshooting.

**5.3.8 IT IS NECESSARY TO CONTROL** temperatures at various points of the engine and throughout the cooling systems. This may be done by bypassing some portion of a coolant stream or by changing the flow rate.

**5.3.9 OVERCOOLING CAN CAUSE PROBLEMS.** A warm engine is easier to start and can quickly be brought up to speed and loaded. Warm oil provides better initial oil circulation and lubrication which is vital in cold weather. Heavy fuel oils must be at a temperature related to the viscosity required by the fuel system and injectors. The carburetor and inlet manifold of an SI engine must be warm enough to prevent "icing" and to vaporize the fuel/air mixture. Exhaust gas temperature must be kept above the dew point to prevent condensation and corrosion. An engine running cold will not achieve rated efficiency. Freezing of the coolant can cause breakage or interfere with required flow and circulation.

**5.3.10 CHEMICAL CONTROL** of the various cooling circuits is important. Strainers and filters remove suspended solids. Additives prevent corrosion, mineral scale buildup, organic growth and organic fouling. Periodic sampling and analysis will indicate actual concentrations of undesired materials dissolved in the coolants. Comparison of test results will provide guidance for altering the treatment program. Some untreated freshwater and brackish or seawater promote growth of barnacles, etc., that prevent proper flow and pressures. Visual inspection is recommended when increasing pressure drops indicate fouling. Physical and/or chemical cleaning may be periodically required. Safety precautions must be followed when using most cleaning compounds.

**6. LUBRICATION SYSTEM.** The bearings and moving parts of all diesel engines are lubricated by a full-pressure system, see figure 3-6.

**6.1 SYSTEM ELEMENTS.** Smaller engines are usually self-contained. The smaller engine system will have many of the system elements used in the larger engines, as follows:

- Lube oil having proper properties for the specific engine design.
- Lube oil tank or sump to hold the volume of oil required.
- Oil feed pump(s) driven from the engine to circulate clean cool pressurized oil (5 to 75 psi).
- Oil feed piping, valves and controls to deliver oil to various lube points of the engine.
- Engine internal oil passageways in the crankshaft-piston assembly and in block and head.
- Hot oil sump to collect oil draining
- Hot oil sump pump (return pump) to force hot used oil through purifier and cooler.oil pump, filter filtering and/or
- Oil filter to remove suspended solids, dirt  and sludge.
- Sampling valves for taking samples of oil and filter solids periodically for testing and analysis.
- Transfer systems for adding new oil and removing used oil from the engine lube system.

**6.1.1 LUBE OIL MUST HAVE** certain properties for specific application. It must flow properly at the minimum temperatures (pour point), have proper viscosity (resistance to shear) between moving parts and retain desired viscosity over the range of temperatures in the engine (viscosity index). The oil must resist oxidation (stability) that forms gum and sludge and the associated catalytic effects of engine metals present (especially copper and lithium) in the detergent additives. It must allow sludge particles to disperse and not clump or deposit throughout the engine. It will contain inhibitors to prevent oxidation, a dispersing agent and a detergent to keep surfaces clean.

**6.1.2 THE PHYSICAL SPECIFICATIONS** for crankcase lube oil are not positive indications of suitability. The experience of the engine manufacturer is guidance for recommended oils. The user must choose.

**6.1.3 PERIODIC SAMPLING**, analysis and evaluation of results is important. An out-of-spec problem will be evident. It is also necessary to look for trends that warn of a condition that may become a major problem. An abnormal rise in the wear metals indicates abnormal wear. Increasing sulphur content and acidity indicates that the lube oil is being contaminated by high-sulfur fuel, oil blowby, etc.

**6.1.4 THE LUBE OIL TANK** must be sufficiently large to hold the oil required for the engine. It must be kept clean and closed to prevent contamination of the oil. A vent with flame arrestor should exist. The tank is the reservoir that feeds the oil pumps. The pump suction line should be above any possible sludge or water at the bottom. The tank and all the components of the lube system should be of materials that will not contaminate the oil.

**6.1.5 LUBE OIL PUMPS** circulate the oil at pressure (5 to 75 psi depending on engine design and system pressure losses when cold) through the oil feedline to the engine lube oil header. An auxiliary electrically-driven pump is used prior to starting a cold engine to provide warm oil to all points, especially to heavily loaded main, crank, and wrist pin bearings, to make sure the lubricating film is formed at first movement. This auxiliary pump may also serve as an automatic standby should a normal engine-driven pump system fail. Controls and valving are provided for that changeover. The auxiliary pump is generally used long enough to return the oil from the critical points and to check the pressure, temperature and flow sensors, indicators, and controls to enable engine cranking. Pumps are usually gear-type with pressure regulation. The engine-driven pump speed is directly related to engine speed so that oil flow increases as speed increases.

**6.2 TYPES AND OPERATION.** Large diesel engines use a lubrication system different from that of smaller diesel engines. Because large engines require a large quantity of oil, a separate sump tank is installed to receive oil from the crankcase. The lubricating oil pump draws oil from the sump tank through the strainers. Oil is then discharged, under pressure, into the oil cooler.

**6.2.1 THE OIL THEN** goes to a header, located on the engine, with branches leading to the various parts of the system. Leads extend from the header to each main bearing. After the oil has been supplied to the main bearings, it passes through a drilled passage in the crank web. The oil then passes through a hole in the crank bearing journal to the connecting rod bearing and up through a drilled hole in the connecting rod to the wrist pin. At the wrist pin, the oil, in some engines, passes through a spray nozzle for splash lubrication against the underside of the piston for cooling. The oil then drains down to the engine crankcase and returns to the pump. Other branches from the header rnay supply oil to the gear trains, camshafts and bearings, rocker arms and push rods, cylinder walls, turbo-chargers, blowers, and in some engines, to an oil-cooling system for pistons. Engines may vary in many details, but the principles are the same in all.

**6.2.2 LUBRICATING SYSTEMS** of small engines usually are self-contained. The crankcase or a separate oil pan underneath the engine contains all the oil used in the system. Figure 3-8 is a cross section of a diesel engine, showing lube oil flow.

**6.2.3 PROCESS.** The diesel engine lubrication system must circulate, filter, and cool large quantities of lubricating oil. Figure 3-9 shows a schematic arrangement of the main components of a diesel lubrication system. The arrows show the flow of lube oil through the system.

**6.2.4 OIL STORAGE.** All high-speed engines and most medium and low-speed engines use the crankcase base or a sump integral with the crank-case for storing lubricating oil. Several engines operate with a so-called dry crankcase to avoid crankcase oil fog that may cause excessive cylinder lubrication. Such engines must have an outside sump tank placed so that oil from the crankcase will drain into it. One design has an elevated, closed pressure tank to which oil is pumped from the crankcase. Open, elevated tanks and two sets of pumps are also used. Sump capacities vary with horsepower.

**6.2.5 LUBE OIL PUMPS.** In most engines, an engine-driven rotary pump supplies pressure needed to circulate oil through the engine lubrication system. Oil pressure varies from 5 to 60 pounds, depending on diesel engine type. The pressure depends on the amount of clearance in the bearings and the capacity of the pump.

**6.2.6 TYPES OF PUMPS.** Lubricating oil pumps are usually built into and driven by the engine. In high speed engines, the oil pump is usually placed in the crankcase sump and driven from the camshaft by a vertical shaft. In larger engines, the pump can be chain-driven by the crankshaft, or mounted at the end of the engine, either inside or outside the crankcase, and driven by the crankshaft. In other engines, the pump is mounted on the end and driven from the camshaft gears. Larger diesel engines frequently have an auxiliary, motor-driven pump that circulates oil to the bearings before the engine is started. As soon as the engine is up to speed, the pump shuts down. The auxiliary pump also serves as an emergency lubricating oil pump in case the engine-driven pump fails. Finally, the auxiliary pump circulates the oil for a time after the engine is shut down to cool bearings, journals, and pistons. When this method is used, a check valve in the discharge line of the auxiliary pump is necessary to prevent the oil from flowing back when the engine comes up to speed and the auxiliary pump is shut down. The check valve also prevents loss of oil in case of leakage.

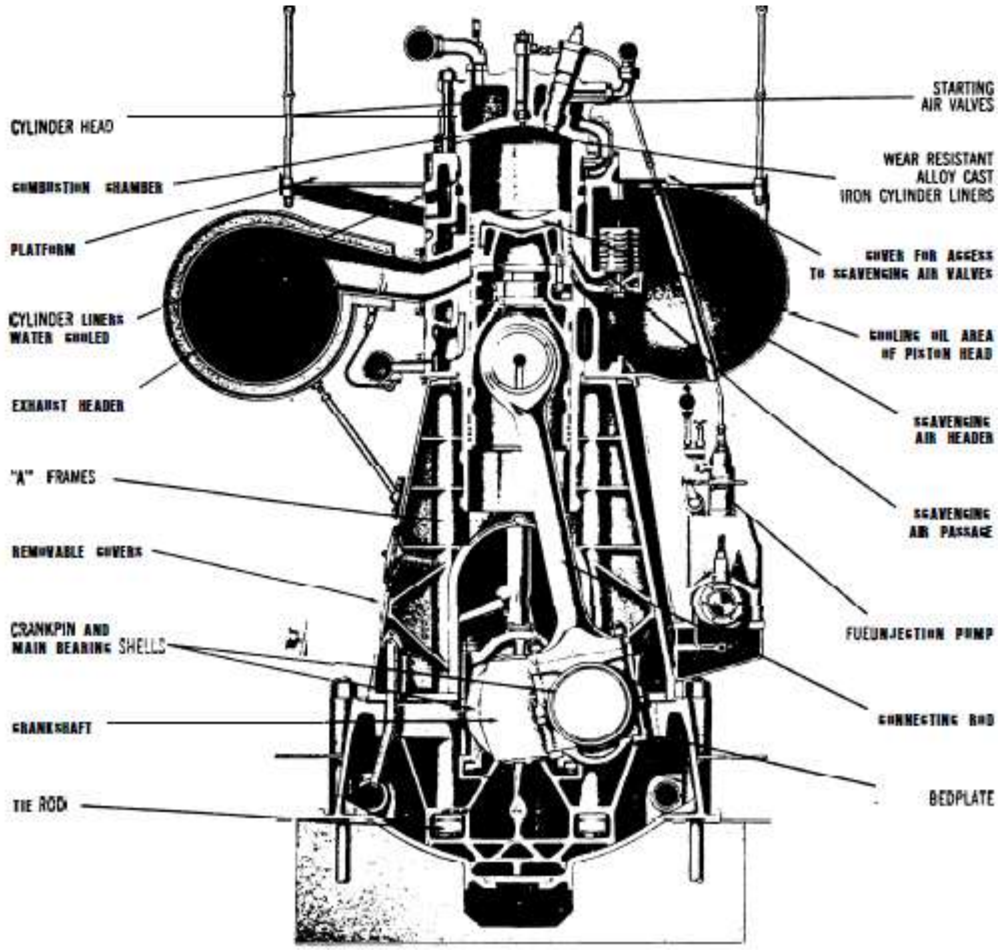



Figure 3-8

Cross Section of a diesel engine showing chamber for lubricating oil collection

**6.2.7 HEATING.** Circulating lubricating oil absorbs heat from the engine. Frictional heat is absorbed from the bearings. The oil film on the cylinder walls absorbs heat from the combustion space before this oil film drains into the crankcase. Heat must be dissipated by a cooler if the temperature is to be kept below 230” Fahrenheit. At higher temperatures, oil oxidizes and sludge forms. An oil cooler is necessary when heat dissipated from the oil (by conduction through the walls of the sump and by contact with water-cooled surfaces in the engine) is insufficient to keep the temperature below manufacturer’s recommendations. A cooler is particularly necessary for engines having oil-cooled pistons.

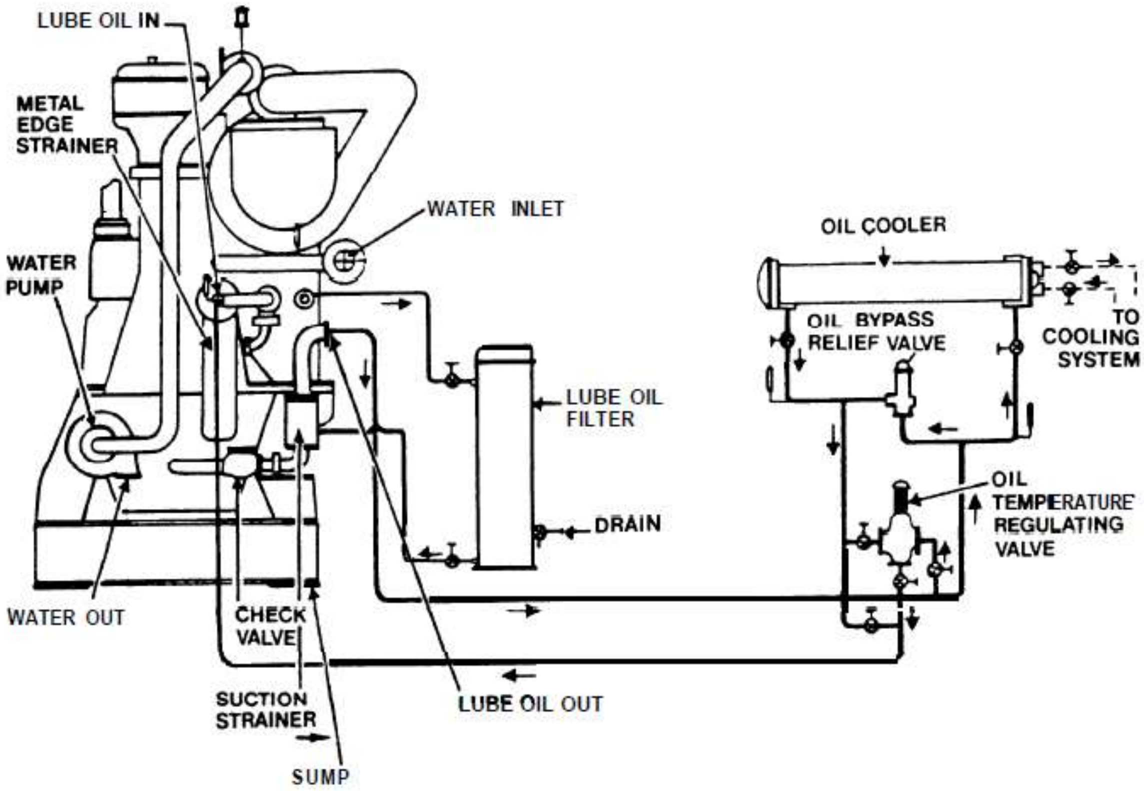



Figure 3-9

Diesel engine lubrication system

**6.2.8 COOLERS.** The oil cooler should be placed in the oil circuit after the lubricating oil filter. The filter then handles hot oil of lower viscosity than if it received cooled oil. The filter performance is better and the pressure drop through it is less with this arrangement. Coolers are usually mounted on the side of the engine or on the floor alongside of the engine base. Cooling water passes through the cooler before entering the engine jackets. Exceptions, such as placing the oil-cooling coils in the water jackets at one end of the engine, are permissible. Also, the coils may be placed in the side jackets. Some designs have the coil tubes in the cooling water header, while in others, water entering the cooler is bypassed around the jacket system.

**6.2.9 OIL FILTERS.** Proper installation and maintenance of oil filters and mechanical operation of the engine are equally important for treatment of oil. Prevention of contamination and removal of contaminants should be coordinated. Because high-detergent oils are used in engines, the purification system should not remove the additive. Cellulose filter cartridges do not remove the additive, but a fuller's earth filter does. In large engine installations, a centrifuge may be used with filter purifiers, or large continuous oil purifiers may be used in lieu of the centrifuge. Centrifuging does not remove acids because acidic compounds have approximately the same specific gravity as oil. Batch settling effectively removes organic acids from oil, improving its neutralization number. When purifiers are used, they should be used in addition to, not in place of, lube oil filters.

**7. STARTING SYSTEM.** The starting system for diesel engines described in this discussion must perform as follows for automatic start-up when primary electric power fails: compress the air in the combustion chambers and deliver fuel for combustion. To do this, the starting system must rotate (crank) the engine at a speed sufficient to raise the cylinder air charge to the fuel igniting temperature. See figure 3-6.

**7.1 TYPES.** Two types of starting systems are available for the required automatic start-up capability: electric starting and air starting.

**7.1.1 ELECTRIC STARTING.** Most small diesel engines use an electric starting system. This type of system is generally similar to a starter for an automotive gasoline engine. Smaller diesel engines use a l2- volt battery-powered system for cranking. Starter and battery systems of 24, 32, and 48 volts are often used for larger engines. A typical system consists of\ storage batteries (as required for voltage output) connected in series, a battery charging system, and the necessary grounding and connecting cables. See figure 3-10.

**7.1.2 AIR STARTING.** Some larger engines may use an air starting system. Compressed air at a pressure of 250 or 300 psi is delivered to the working cylinder's combustion chambers during the power stroke. This action results in positive and fast rotation (cranking). Depending on the manufacturer's design, compressed air can be delivered to all or selected cylinders. This type of system requires an air compressor and receivers or air bottles for storage of compressed air.

**7.1.3 AIR STARTER MOTOR.** Pneumatic air starter motors are highly reliable. Air starter motors develop enough torque to spin the engine at twice the cranking speed in half the time required by electric starter motors. Compressed air at a pressure of 110 to 250 psi is stored in storage tanks, regulated to 110 psi and piped to the air motor. A check valve installed between the compressor and the storage tanks will prevent depletion of compressed air should the plant system fail. Air starter motors are suitable

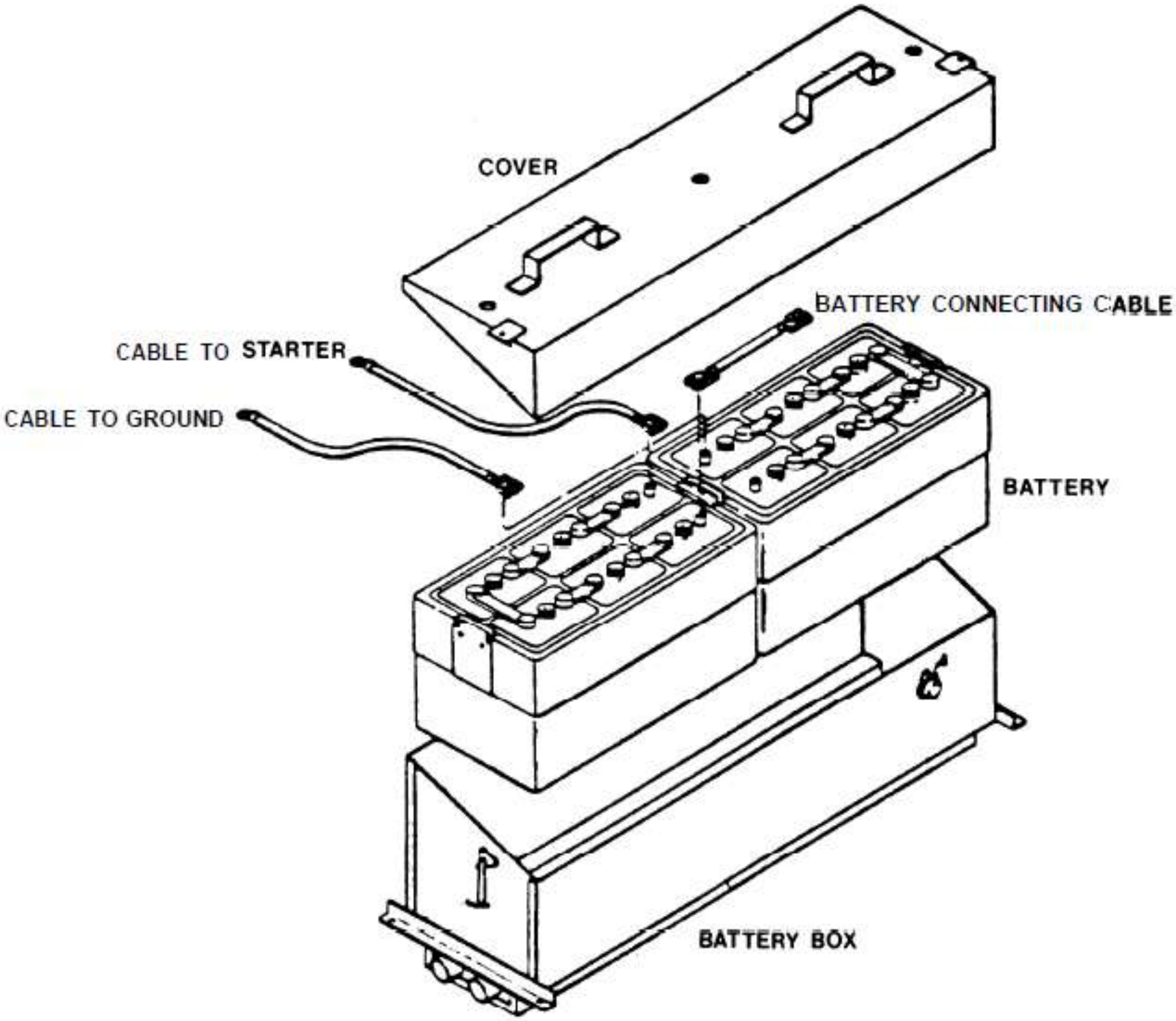



Figure 3-10
Battery for engine starting system.

on diesel engine driven generators ranging from 85 kW up to the largest diesel engine generator.

**8. GOVERNOR/SPEED CONTROL.** A diesel engine used in an auxiliary generator must have a governor to regulate and control engine speed. Since an automatic governor functions only with a change in speed, constant engine speed may not be totally possible and "hunting" can occur due to over-correction. The governor's sensitivity is determined by the minimum change in speed of the prime mover which will cause a change in governor setting; its speed regulation is the difference in generator speeds at full-load and no-load divided by the arithmetical mean of the two speeds.

**8.1 USUALLY, THIS RATIO** is stated as a percentage, with synchronous speed considered rather than mean speed. For example, a generator with a synchronous speed of 1,200 rpm, operated at 1,190 rpm when fully loaded and 1,220 rpm with no load, has 2.5 percent speed regulation.

**8.2 THE GOVERNOR MUST BE CAPABLE** of speed adjustment so the proper governed speed can be selected. In most governors, this adjustment is made by changing the tension of the main governor spring. The governor should also be adjustable for speed regulation so the droop of the speed-load curve can be altered as required to suit operating conditions. Determine the curve by observing the generator speed or frequency at various loads and plotting them as abscissa against the loads (from no-load to full-load) as ordinates. The curve droops at the full load end (hence, the expression "speed droop" of the governor).

**8.3 AN EXAMPLE OF SPEED DROOP** characteristics is shown in figure 3-11. The characteristics are for a mechanical governor but the same principles can be used for other engine/governor applications. The chart is based on a six percent speed droop governor on an engine running at rated speed at no load. When full load is applied, engine speed drops to 94 percent (94%) of rated value (line B). The engine can be brought to rated speed at full load by resetting the governor (line A). However, with the load removed, engine speed would increase beyond its rated limit. Intermediate speed settings are shown by lines C and D. Line E shows speed droop at 50 percent (50%) load.

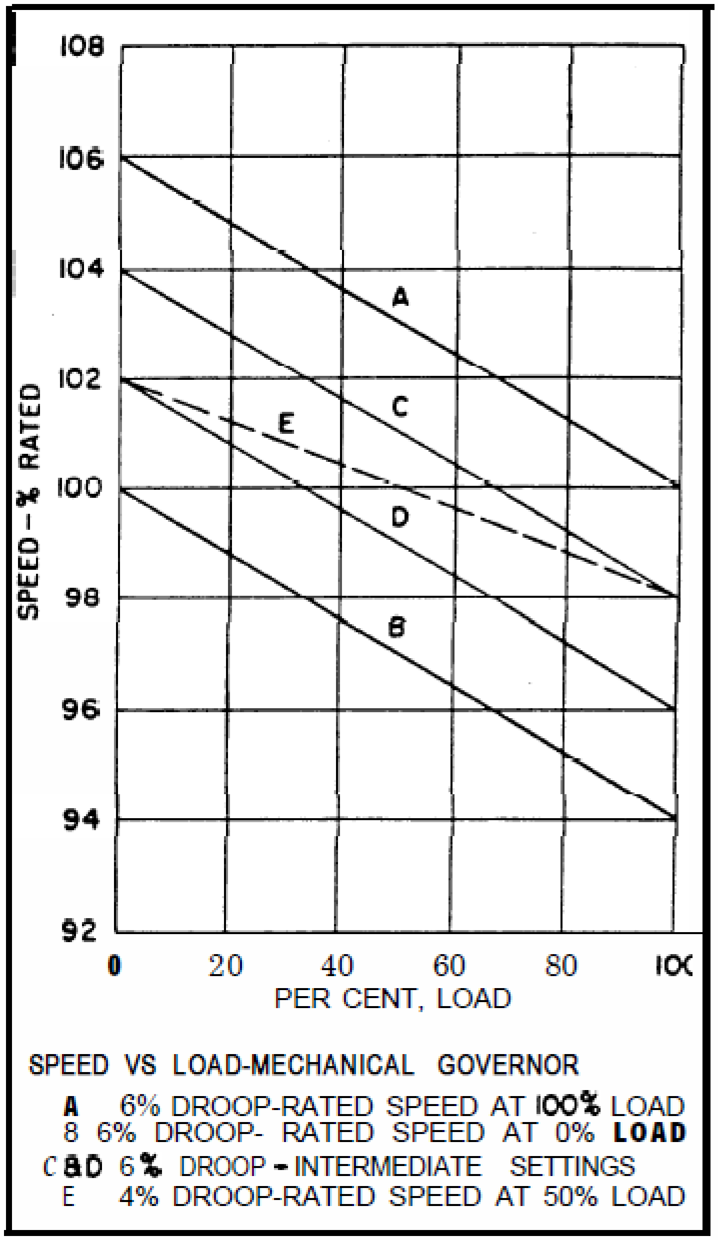



Figure 3-11

Chart of speed droop characteristics.

**8.4 SPEED DROOP CAN BE DETERMINED** quickly by loading the generator to full-load, observing the speed, unloading the generator, and again observing the speed. Speed droop is usually adjusted by lengthening or shortening the governor operating levers, changing the ratio between governor movement and throttle or gate movement.

**8.5 ALTERNATING CURRENT (AC) GENERATORS.** Governors of prime movers driving AC generators which operate in parallel with other generators must have enough speed regulation or speed droop to prevent surging of the load from one generator to another. Ordinarily, three to five percent speed regulation is adequate. Some governors have anti-surging devices to damp out the surges. Speed regulation should be increased if the surges continue. Speed regulation of governors controlling AC generators affects the frequency and the load division between generators but has almost no effect upon voltage.

**8.6 DIRECT CURRENT (DC) GENERATORS.** Regulation of DC generators affects voltage regulation and the division of load between generators. In general, the speed regulation of generators operated in parallel should be the same for each machine. Speed regulation for generators operating individually should be as favorable as possible without causing generator surge resulting from sudden load changes. Ordinarily, 2.5 percent speed regulation is satisfactory. Voltage regulation of DC generators may be accomplished through adjustment of the speed droop of the governor.

**8.7 TYPES OF GOVERNORS.** Usually four types of governors are used; mechanical, hydraulic, pneumatic, and electronic. When speed regulation must be more precise, such as sites where no more than 0.8 percent variation is permitted, an electronic (isochronous) governor is used.

**8.7.1 THE MECHANICAL GOVERNOR** used in small aircooled engines may be part of the fly-wheel. The governor in multicylinder engines is usually a separate assembly driven by gear or belt from a camshaft or crankshaft. A typical mechanical governor, shown in figure 3-12, operates as follows: the governor drive gear (2) drives the governor shaft (10) and the governor weights (4). Centrifugal force moves the weights away from the shaft which push the operating-fork riser (6) against the operating fork (ll), rotating the operating-fork shaft (7) and moving the governor arm (9). In the external view, the governor spring (A) is connected to the governor arm and opposes movement of the governor weights away from the shaft. Adjusting screw (c) adjusts the tension of the governor spring, establishing the speed at which the prime mover operates. The greater the governor-spring tension, the lower the governed speed. The auxiliary adjusting screw (D) adjusts the droop of the governor. Turning this screw in closer to the arm decreases the droop of the governor; this screw should be turned in as far as possible without allowing the engine to surge. Auxiliary adjusting screw (B) is turned in to damp out surging of the engine at light-load or no-load; it should not be turned in so far that it increases the speed of the generator at no-load.

**8.7.2 THE HYDRAULIC GOVERNOR** (see fig 3-13) is used on large prime movers as well as diesel engines as small as 100 hp. The governor usually includes: a speed-responsive device, usually flyweights; a valve mechanism; a regulating cylinder and piston; and a pressure pump and relief valve. The assembly is adjustable for various ranges of speed and sensitivity. The hydraulic principle provides greater power than could be obtained from a mechanical type. Since the flyweights only control an easily moved pilot valve (which in turn controls the hydraulic action), the governor can be made to operate accurately and smoothly. Remote control and automatic equipment can be applied to the hydraulic governor.

**8.7.2.1 THE HYDRAULIC GOVERNOR** requires pressurized oil for operation. This oil can come from the engine or from a separate sump in the governor. Oil is admitted to an auxiliary oil pump in the governor. The auxiliary pump furnishes necessary pressure to actuate the governor mechanism. In the governor shown, the fuel to the engine is decreased by the action of the fuel-rod spring (10) on the fuel rod ( 12) and increased by the opposing action of the hydraulic serve piston (14), the admission of oil to which is controlled by a pilot valve (4). The pilot valve is controlled by flyweights of the governor (5) which are driven by the governor shaft through gearing to the engine. The centrifugal force of the flyweights in rotation is opposed by the speeder spring (6), the compression of which determines the speed at which the governor will control the engine. The speeder-spring compression is adjusted through the rotation of the speed-adjusting shaft (8) which raises or depresses the spring fork (7) through its linkage lever.

**8.7.2.2 THE DROOP** of the speed-load characteristic is adjusted by changing the effective length of the floating lever (11). This is accomplished by moving the droop-adjusting bracket forward or backward in the slot of the floating lever. The effective length of the lever should be shortened to decrease the speed droop and lengthened to increase the speed droop.

**8.7.3 THE PNEUMATIC GOVERNOR** (air-vane type) is used in certain small generator plants (see fig 3-14). The engine flywheel includes an integral fan which forces air outward from the drive shaft. The amount of air flowing from the engine depends on engine speed. A movable air vane is placed in the air stream. The air vane (blade) acts as a governor since the air pressure depends upon engine speed. The air pressure on the vane is opposed by a governor spring and these forces operate through linkage to control the throttle of the engine.

**8.7.4 ELECTRONIC (ISOCHRONOUS) SPEED CONTROL** is the maintenance of constant engine speed independent of the load being carried (zero droop). An isochronous governor will maintain, or can be adjusted to maintain, constant engine speed (within 0.2 percent variation). This type of governor can be a combination of a conventional hydraulic governor and an electronic load-sensing system, or an all-electric system.

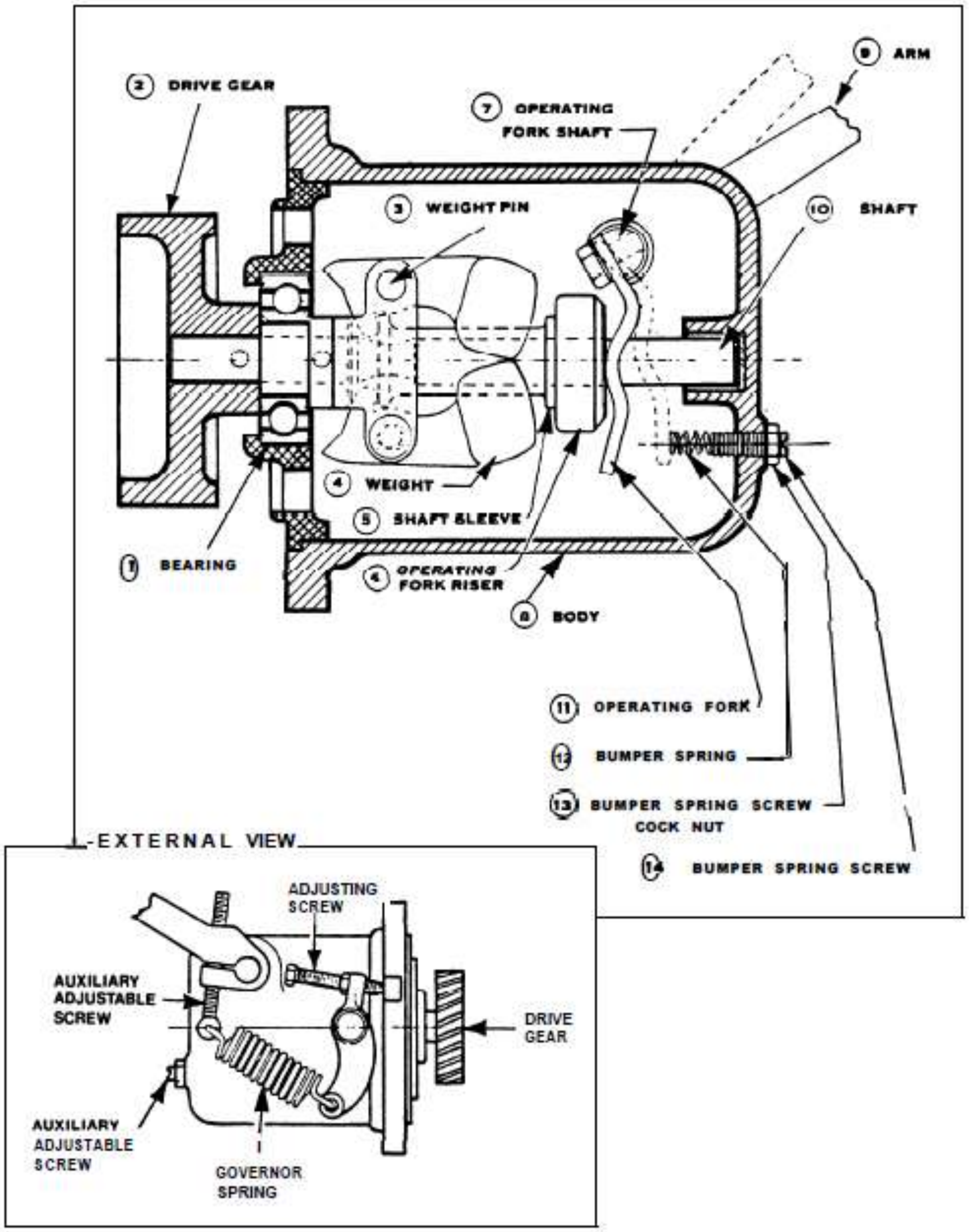
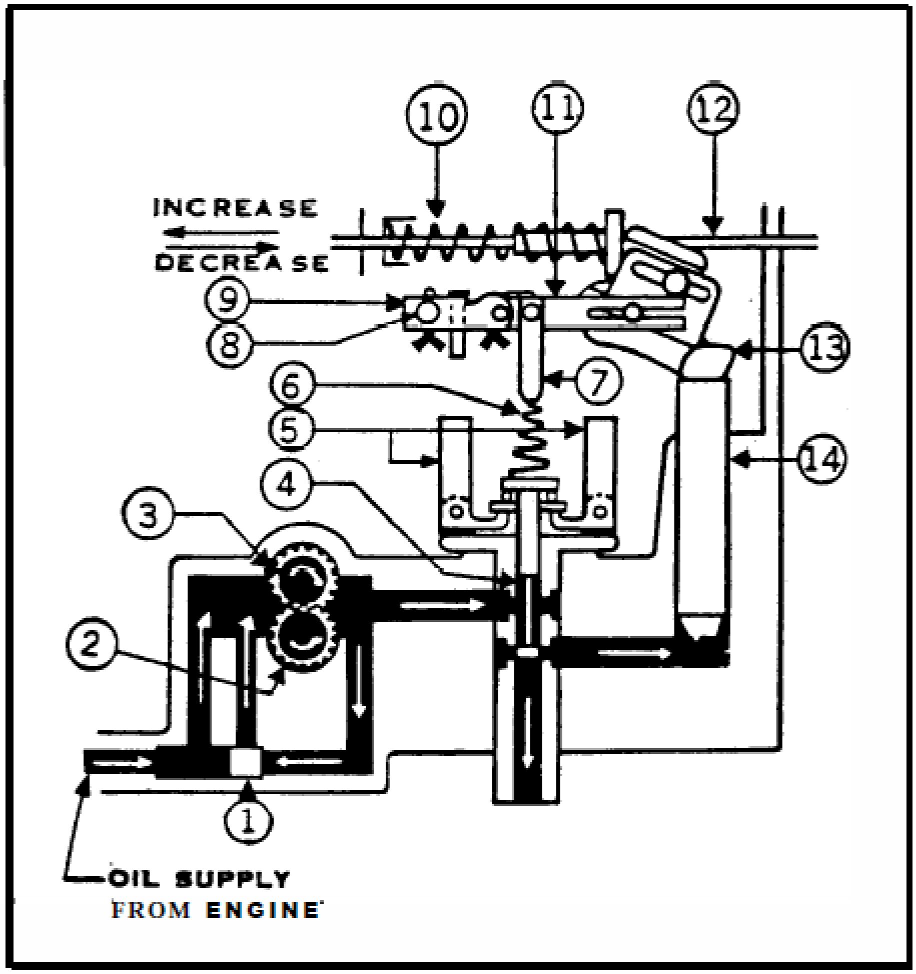



Figure 3-12

Mechanical Governor




*1) PLUNGER, 2) GEAR PUMP DRIVE, 3) GEAR PUMP IDLER, 4) PLUNGER PILOT VALVE, 5) FLYWEIGHT, 6) SPEEDER SPRING, 7) SPRING FORK, 8) SPEED-ADJUSTING SHAFT, 9) SPEED-ADJUSTING LEVER, 10) SPRING, 11) FLOATING LEVER, 12) FUEL ROD, 13) TERMINAL LEVER, 14) SERVO PISTON*

Figure 3-13

Hydraulic Governor.

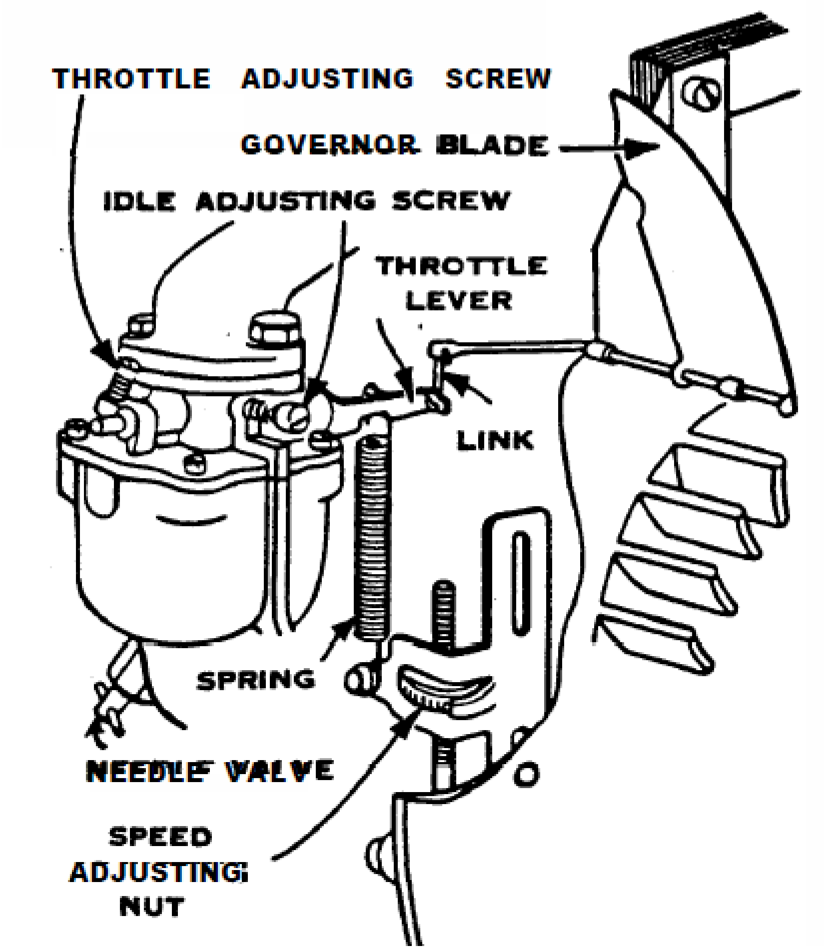



Figure 3-14

Carburetor and pneumatic governor.

**8.7.4.1 SPEED CONTROL BY THE HYDRAULIC** governor depends on variation in centrifugal force created by flyweights (centrifugal forces are not used in electric types). This force operates a piston-type pilot valve which controls the flow of high-pressure oil to a servomotor, thereby operating fuel controls.

**8.7.4.2 THE ISOCHRONOUS SYSTEM** uses electronic sensing and amplifying devices that actuate a type of servomotor throttle control. The system is used with power generation where precise frequency control is required. An isochronous system may be sensitive to frequency changes (engine speed) or to both frequency and load. When responsive to load changes, the system corrects fuel settings before load changes can appreciably modify engine speed or frequency.

**9. AIR INTAKE SYSTEM.** Approximately 15 pounds of air is required to burn one pound of fuel. Accordingly, the air requirement for a 2000 horsepower engine is about 3600 cubic feet per minute. The same horsepower-to-air relationship applies to engines for other power ratings. Intake air carries dust particles, water vapor and other foreign material. Since these materials can damage moving parts within the engine, filtration of the intake air is necessary. A 2000 horsepower engine, breathing air containing three parts per million dust contamination, would take in 25 pounds of foreign material in 1000 operating hours. An air intake system must collect, filter, and distribute the required air to the engine cylinders. This must be accomplished with a minimum expenditure of energy (pressure drop). The objective of air filtration is the reduction of engine component wear. Several types of air filters or air cleaners are used. The pleated-paper type are strainers, porous enough to pass air but able to remove solid particles larger than 0.002 of an inch. Larger engines use an oil bath air cleaner (see fig 3-15). In oil-bath cleaners air is drawn through an oil bath. Solid particles are trapped and settle in the unit's bottom pan.

**9.1 SUPERCHARGING.** Supercharging increases the amount of air taken into a working cylinder. This provides the injected fuel oil with more oxygen to enable combustion of a larger charge of air/fuel mixture. Power output of a certain size engine is thereby increased, enabling use of smaller engines where space prohibits larger engines.

**9.1.1 ADVANTAGES.** The power output of a naturally aspirated engine is limited by the normal pressure and oxygen content of the atmosphere. When supercharging is used, the intake valve (port) closes with the cylinder under the initial pressure. Supercharging is particularly effective at higher altitudes. The supercharged engine can develop greater horsepower than the standard naturally-aspirated unit. The fuel consumption of a supercharged unit will not exceed that of comparable horsepower sizes of naturally-aspirated units.

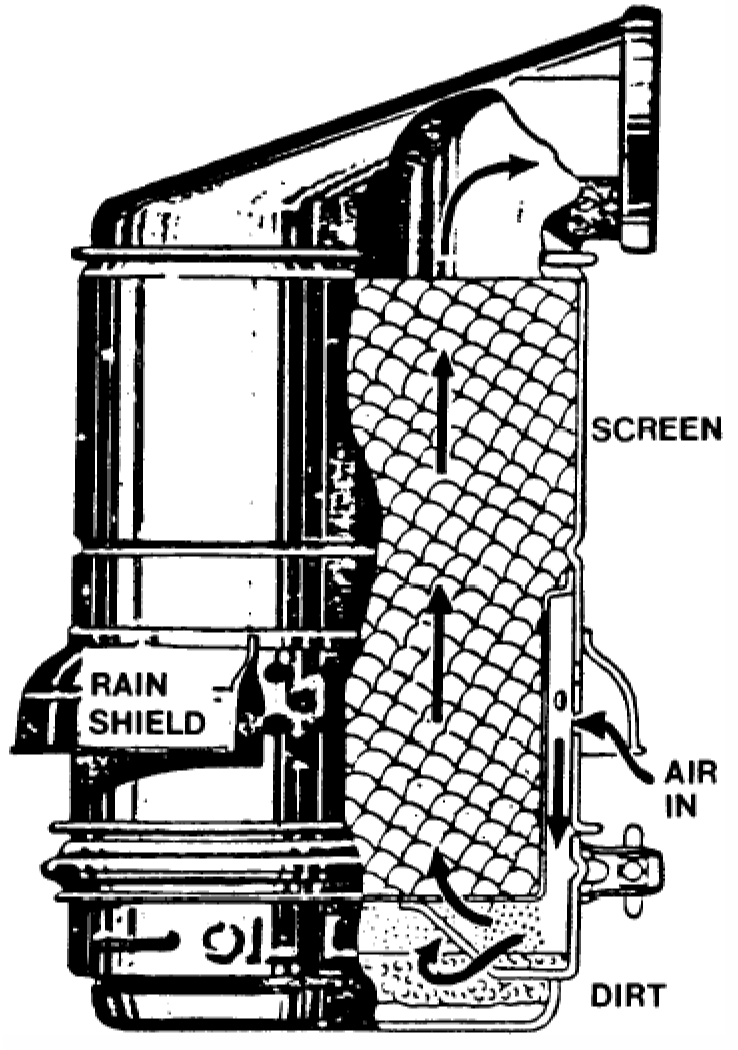



Figure 3-15
Oil bath air cleaner

**9.1.2 METHODS**. The most successful method of supercharging is the use of a turbocharger driven by exhaust gas (see fig 3-16). The heat and energy pulsations in the exhaust gas, which are usually lost in the exhaust silencer, are used to drive a single-stage centrifugal turbine. The exhaust gas turbine is coupled to a centrifugal compressor that compresses the air to a pressure of four or five psi. The engine's pressurized air is then delivered to the individual cylinders through the intake manifold.

**9.1.3 DISADVANTAGES.** Although the supercharged engine has many advantages over non-supercharged engines, its disadvantages are not insignificant. The turbocharger is another piece of equipment to maintain and operate. It operates at varying speeds depending on engine load, barometric pressure, inlet air temperature, exhaust temperature, smoke content of the exhaust, or accumulations of dust and dirt on the impeller and diffuser. It may operate at very high speed (up to 120,000 rpm) with a full load on the engine and thus be subjected to all the troubles of high-speed equipment. With proper maintenance, however, the turbocharger can be operated very successfully. If the turbocharger fails, the engine can usually be operated at reduced load as a non-supercharged engine. The turbocharger can be partially dissembled and the opening blocked off, but the coolant should be allowed to circulate through the supercharger.

**9.1.4 OPERATING INSTRUCTIONS.** Manufacturer's instructions must be followed to ensure proper operation of superchargers. Filtered air only should enter the air inlet, because foreign matter can cause rotor imbalance and damaging vibration. The manufacturer's recommendations for lubrication must be followed. Proper lubrication is necessary because the unit operates at high speed and at high temperature. Not more than 15 seconds should elapse between the start of rotation and an oil pressure indication of 12 to 71 psi. Coolant circulation through the turbocharger should be regulated so the temperature rise does not exceed 30" Fahrenheit at full engine load. A rise in excess of 30" Fahrenheit indicates faulty circulation. Coolant should be allowed to circulate through the turbocharger for about 5 minutes after the engine is shutdown.

**9.1.5 ASPIRATION.** The term "naturally-aspirated" is applied to engines that are not supercharged. A four stroke cycle engine performs its own air pumping action with the piston intake stroke. When it is supercharged, a four-stroke engine with a blower or turbocharger provides pressure in the intake manifold greater than atmospheric. The increased pressure in the intake manifold is referred to as "boost". Two stroke cycle engines require an air supply under pressure to provide scavenging air.

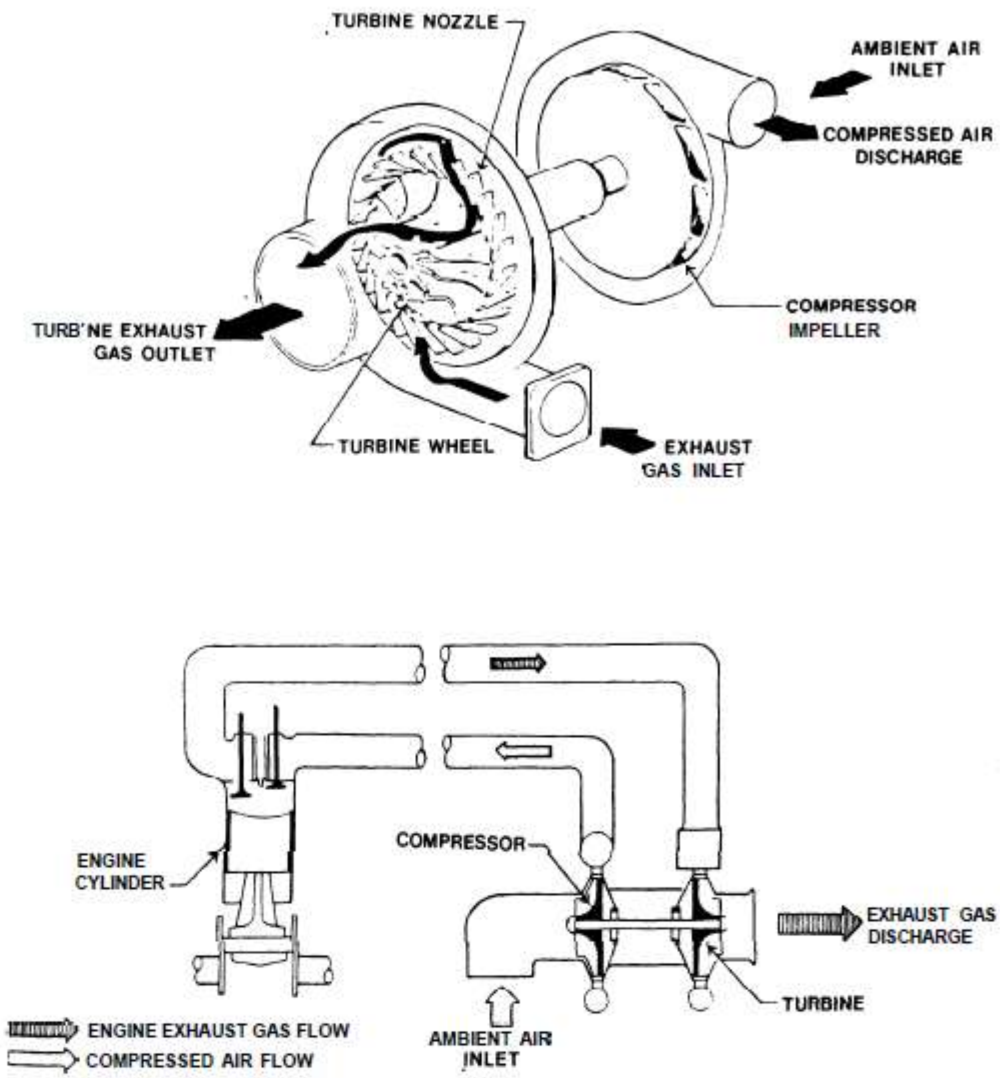



Figure 3-16

Diagram of turbocharger operation.

**10. EXHAUST SYSTEM.** The exhaust system consists of the engine exhaust manifold and includes piping, expansion joints, silencers, and exhaust pipe. Also the system may include exhaust waste heat recovery equipment. The purpose of the system is to remove exhaust gas from engine cylinders to the atmosphere. Parts of the system are shown in figure 3-6.

**10.1 LEAK-FREE.** Exhaust systems must be leak free to protect personnel from asphyxiation, and equipment from fire and explosion. Exhaust from gasoline engines can contain dangerous carbon monoxide. Diesel engine exhaust includes objectionable smoke and odors. On supercharged engines, leaks ahead of the turbine cause a loss of power.

**10.2 PIPING.** Exhaust piping must be the correct size to minimize exhaust back pressure. Connections between exhaust manifold and piping should have an expansion joint and the exhaust pipes should slope away from the engine. Also the exhaust pipes should have suitable devices to prevent entry of rainwater. The length of tail pipes from silencer to atmosphere should be kept to a minimum.

**10.3 SILENCERS.** Silencers are used to reduce or muffle engine exhaust noise. Silencing engine exhaust sounds consists of trapping and breaking up the pressure waves. Usually, a cylindrical unit with baffles, expansion chambers, and sound absorption materials is used.

## 11. SERVICE PRACTICES.

**11.1 MAINTENANCE PROGRAM.** Service practices for diesel engines consist of a complete maintenance program that is built around records and observations. The maintenance program includes appropriate analysis of these records.

**11.1.1 RECORD KEEPING.** Engine log sheets are an important part of record keeping. The sheets must be developed to suit individual applications (i.e., auxiliary use) and related instrumentation. Accurate records are essential to good operations. Notes should be made of all events that are or appear to be outside of normal range. Detailed reports should be logged. Worn or failed parts should be tagged and protectively stored for possible future reference and analysis of failure. This is especially important when specific failures become repetitive over a period of time which may be years.

**11.1.2 LOG SHEET DATA.** Log sheets should include engine starts and stops, fuel and lubrication oil consumption, and a cumulative record of the following:

- Hours since last oil change.
- Hours since last overhaul.
- Total hours on engine.
- Selected temperatures and pressures.

**11.2 TROUBLESHOOTING.** Perform troubleshooting procedures when abnormal operation of the equipment is observed. Maintenance personnel should then refer to log sheets for interpretation and comparison of performance data. Comparisons of operation should be made under similar conditions of load and ambient temperature. The general scheme for troubleshooting is outlined in the following paragraphs.

**11.2.1 INDUSTRIAL PRACTICES.** Use recognized industrial practices as the general guide for engine servicing. Service information is provided in the manufacturer's literature and appendixes B through G.

**11.2.2 REFERENCE LITERATURE.** The engine user must refer to manufacturer's literature for specific information on individual units. For example, refer to table 3-5 for troubleshooting an engine that has developed a problem.

| Cause | Remedy |
|---|---|
| HARD STARTING OR FAILS TO START | |
| Air intake restricted. | Check intake and correct as required. |
| Fuel shut-off closed, low supply of fuel. | Make sure shut-off is open and supply is at proper level. |
| Poor quality fuel. | Replenish fuel supply with fresh, proper quality fuel. |
| Clogged injector. | Clean all injectors, refer to appendix G. |
| Injector inlet or drain connection loose. Engine due for overhaul. | Check all connections and correct as required. Schedule the overhaul and correct as required. |
| Incorrect timing. | Perform timing procedure, refer to appendix G. |
| ENGINE MISSES DURING OPERATION | |
| Air leaks in fuel suction lines. | Check fuel suction lines and correct as required. |
| Restricted fuel lines. | Check fuel lines and correct as required. |
| Leakage at engine valves. | Refer to manufacturer's instructions and correct as required. |
| Incorrect timing. | Perform timing procedure, refer to Appendix G. |
| EXCESSIVE SMOKING AT IDLE | |
| Restricted fuel lines. | Check fuel lines and correct as required. |

Table 3-5

Diesel engines troubleshooting

EXCESSIVE SMOKING AT IDLE

| Cause | Remedy |
|---|---|
| Clogged injector. Leaking head gasket or blowby. Engine due for overhaul. Incorrect timing. | Clean all injectors, refer to appendix G. Refer to manufacturer's instruction and correct as required. Schedule the overhaul and correct as required. Perform timing procedures. refer to appendix G. |
| **EXCESSIVE SMOKING UNDER LOAD** | |
| The same causes for "idle" apply. | The same remedies for "idle" apply. |
| Air intake restricted. | Check air intake and correct as required. |
| High exhaust back pressure. | Check exhaust system and turbocharger; correct as required. |
| Poor quality fuel. | Replenish fuel supply with fresh, proper quality fuel. |
| Engine overloaded. | Reduce load to proper ievel. |
| **LOW POWER OR LOSS OF POWER** | |
| Air intake restricted. | Check air intake and correct as required. |
| Poor quality fuel. | Replenish fuel supply with fresh, proper quality fuel. |
| Clogged injector. | Clean all injectors, refer to appendix G. |
| Faulty throttle linkage or governor setting too low. | Check linkage and governor refer to manufacturer's instructions and correct as required. |
| Clogged filters and screens. | Clean filters and screens. |
| Engine overloaded. | Reduce load to proper level. |
| Engine due for overhaul. | Schedule the overhaul and correct as required. |
| Incorrect timing. Engine requires tune-up. | Perform timing procedure, refer to appendix G. Perform tune-up procedure, refer to appendix G. |

Table 3-5 (continued)

Diesel engines troubleshooting

| | |
|---|---|
| DOES NOT REACH GOVERNED SPEED | |
| The same causes for "low power", apply. | The same remedies for "low power", apply. |
| EXCESSIVE FUEL CONSUMPTION | |
| Air intake restricted. | Check air intake and correct as required. |
| High exhaust back pressure. | Check exhaust system and turbocharger; correct as required. |
| Poor quality fuel. | Replenish fuel supply with fresh. proper quality fuel. |
| Faulty injector. | Clean all injectors, refer to appendix G. |
| Engine overloaded. | Reduce load to proper level. |
| Engine due for over-haul. | Schedule the overhaul and correct as required. |
| Incorrect timing. | Perform timing procedure, refer to appendix G. |
| ENGINE QUITS | |
| Air intake restricted. | Check air intake and correct as required. |

Table 3-5 (continued)

Diesel engines troubleshooting

| Cause | Remedy |
|---|---|
| **ENGINE QUITS** | |
| High exhaust back pressure turbocharger. | Check exhaust system and correct as required. |
| Fuel shut-off closed, low supply of fuel. | Make sure shut-off is open and supply is at proper level. |
| Poor quality fuel. | Replenish fuel supply with fresh, proper quality fuel. |
| Faulty injector. | Clean all injectors, refer to appendix G. |
| **ENGINE SURGES AT GOVERNED SPEED** | |
| Air leaks in fuel suction lines. | Check fuel suction lines and correct as required. |
| Faulty injector. | Clean all injectors, refer to appendix G. |
| Leaks in oil system. | Check for oil leaks, check oil lines, check crankcase drain plug and gasket; correct as required. |
| Engine due for overhaul. | Schedule the overhaul and correct as required. Piston rings or cylinder liners may be worn. |
| **SLUDGE IN CRANKCASE** | |
| Fouled lubricating oil strainer or filter. | Check strainers and filters, remove and service as required, reinstall on engine with new gaskets. |
| Faulty thermostat. | Check coolant thermostats, engine may be too cool. |
| Dirty lubricating oil. | Drain old oil, service strainers and filters, refill with fresh oil. |
| **LUBRICATING OIL DILUTED** | |
| Fuel in lubricating oil. | Check for loose injector inlet or drain connection; correct as required. Drain old oil, service strainers and filters, refill with fresh oil. |
| Coolant in lubricating oil. | Check for internal coolant leaks. Correct as required. Drain old oil, service strainers and filters, refill with fresh oil. |
| **LOW LUBRICATING OIL PRESSURE** | |
| Faulty oil line, suction line restricted, low oil level. | Check oil lines for good condition, fill to proper oil level with fresh oil. |
| Engine due for overhaul. | Schedule the overhaul and correct as required. Piston rings, crankshaft bearings, or cylinder liners may be worn. |
| **ENGINE RUNNING TOO HOT** | |
| High exhaust back pressure. | Check exhaust system and turbocharger, correct as required. |
| Faulty thermostat. | Check coolant thermostats; correct as required. |
| Low lubricating oil level. | Fill to proper level with fresh oil. |
| Engine overload. | Reduce load to proper level. |
| Faulty cooling system component (pump, hose, radiator fan belt). | Check components; correct as required. Fill cooling system to proper level with coolant. |

Table 3-5 (continued)

Diesel engines troubleshooting

| Cause | Remedy |
|---|---|
| **ENGINE RUNNING TOO HOT** | |
| Low coolant level. Air in system. | Refer to appendix D. |
| **ENGINE KNOCKS** | |
| Poor quality fuel. | Replenish fuel supply with fresh, proper quality fuel. |
| Air leaks in fuel suction lines. | Check fuel suction lines and correct as required. |
| Engine overloaded. | Reduce load to proper level. |
| Engine running too hot. | Repeat the procedures for "too hot", above. |
| Faulty vibration damper or flywheel. | Correct as required, refer to manufacturer's instructions. |
| Engine due for overhaul | Schedule the overhaul and correct as required. |

Table 3-5 (continued)

Diesel engines troubleshooting

## 12. OPERATIONAL TRENDS AND ENGINE OVERHAUL.

**12.1 TRENDING DATA.** Usually, a graphic presentation of data simplifies detection of a trend toward deteriorating engine performance. Samples of graphic aids are shown in figures 3-17 and 3-18. These include plots of fuel and lubricating oil consumption versus electric load (power production), monthly pressure checks (engine parameters), and maintenance data showing cylinder wear and crankshaft deflection. Interpretation of data and details are provided in the specific engine manufacturer's literature. These kinds of data aid in developing criteria for equipment performance and determining the need for engine overhaul or other repair.

**12.1.1 SAMPLES OF INFORMATION** appearing in figure 3-17 are as follows:

- "A" on the chart may indicate lack of operating hours.
- "B" on the chart may indicate a peak value or seasonal characteristic.
- "C" on the chart may indicate the result of frequent starts or stops. "D" on the chart indicates a steady improvement.
- "E" on the chart shows lubricating oil consumption. The steady decline at "F" may indicate a developing engine problem (i.e., oil control ring failure, lube oil leakage into combustion areas, or excessive oil feed).

**12.1.2 SAMPLES OF INFORMATION** appearing in part A of figure 3-18 are as follows:

- "A" on the chart may indicate faulty fuel injectors, or deviations in fuel timing.
- "B" on the chart (sharp rise in compression) can be caused by carbon build up or may indicate new piston rings were installed.
- "C" on the chart may indicate a developing engine problem.
- ("D" on the chart indicates engine governor positions relative to "A", "B", and "C".

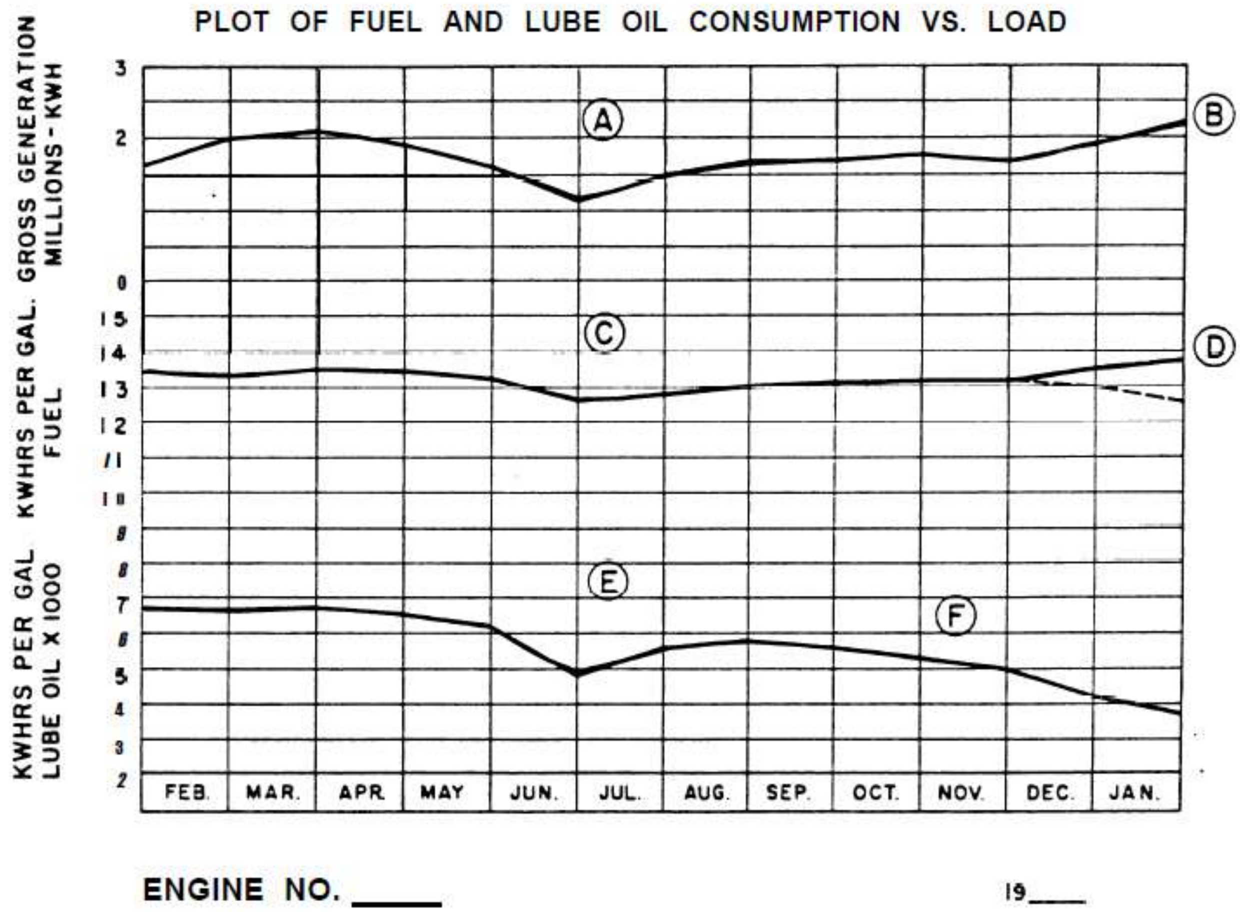



Figure 3-l7

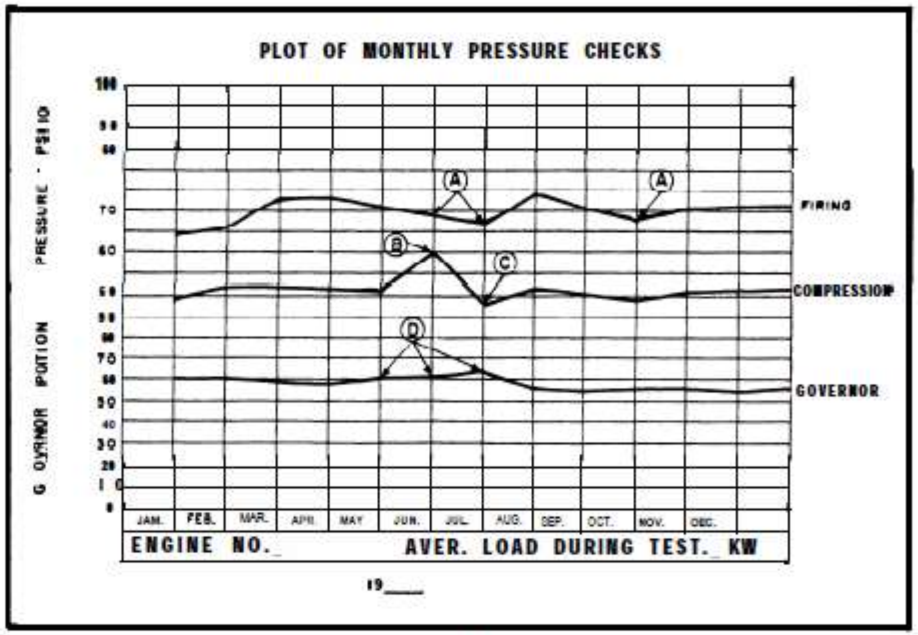
Performance data plots

**12.2 ENGINE OVERHAUL.** An engine consists of structural parts and moving parts. Structural parts are those having no movement relative to each other. They do not involve clearances, adjustments, or lubrication. These parts consist of the following: foundation, bedplate, foundation bolts, frames, cylinders and block, cylinder heads, covers and associated gaskets, and auxiliary housings. Moving parts are those that normally require fitting and/or clearance adjustment. These parts consist of the following: crankshaft (including journal surfaces, counterweights, gears, and flywheels), main bearings, thrust bearings, camshafts and bearings, connecting rods and bearings, pistons (including rings and pins), timing gear mechanisms, and auxiliary or accessory drives. All of these parts are engineered and designed by the engine manufacturer to perform a particular task. When the need to overhaul an engine is indicated by operational malfunctions (refer to the troubleshooting table) consult the specific manufacturer's literature for instructions.

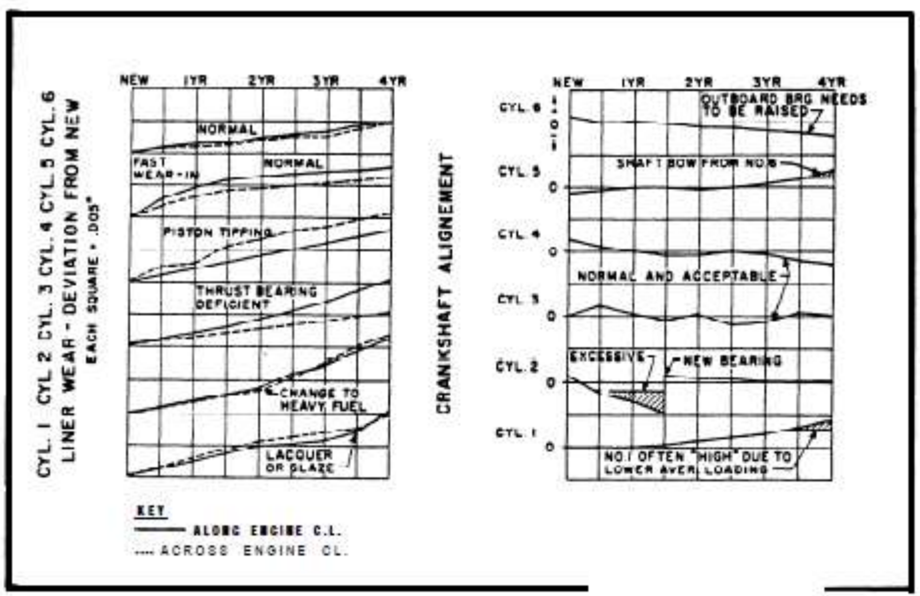
**12.3 OVERHAUL PROCEDURE.** Engine overhaul requires disassembly of the engine. Verify that all engine parts comply with the manufacturer's specifications and tolerances.

**12.3.1 INSPECT STRUCTURAL PARTS** as follows:

- Foundations for deformation and cracks.
- Bedplate for cracks and distortion; bearing supports for good condition.
- Foundation bolts for tightness and general good condition including straightness.
- Frames for cracks, distortion, and general good condition.
- Cylinders and cylinder blocks for cracks; water jacket areas for corrosion, scale, and rust; machined surfaces for smoothness.
- Cylinder heads for cracks; water jacket areas for corrosion, scale, and rust; valve seats for cracks; machined surfaces for smoothness.
- Covers and gaskets for distortion and cracks; use satisfactory gaskets only after annealing; use new seals and gaskets other than copper.




A.




B.

A) 'AS-FOUND" PRESSURES

B) MEASUREMENTS OF MECHANICAL WEAR INDICATORS.

Figure 3-18

Maintenance data plots

**12.3.2 INSPECT MOVING PARTS** as follows:

- Crankshaft for out-of-alignment condition; journal surfaces for highly polished condition and absence of scratches, nicks, etc.; and counterweights, gears, and flywheels for proper condition. Verify that crankshaft complies with manufacturer's requirements. An engine crankshaft is a costly and vulnerable component. Special care in handling is required. Accurate alignment is essential to good engine operation. Removal or installation may require hoisting. Refer to the manufacturer's instructions for details and proper procedures.

- Main bearings for highly polished condition, cracks, deformation and absence of scratches, nicks, etc.

- Thrust bearings for cracks and deformation; surfaces for smoothness and absence of scratches and nicks.

- Camshaft cams and cam faces for worn or deformed condition; journal surfaces and bearings for highly polished condition and absence of scratches, nicks, etc; and cam contours and cam followers for good condition.

- Connecting rods for cracks or other flaws by magnaflux or dye penetrant method and for bending and for parallelism; bearings for highly polished condition and absence of scratches, nicks, cracks, and deformation.

- Pistons for cracks and warped condition; verify pistons, rings, and pins comply with manufacturer's requirements; and rings and pins for general good condition.

- Timing gear mechanisms for good condition; backlash for manufacturer's tolerance requirements; and gear teeth for general good condition.

- Auxiliary or accessory drives for good operating condition. Consult the specific manufacturer's literature for instructions.

**12.4 REPAIR PARTS AND SUPPLIES**. Certain repair parts and supplies must be available for immediate use. Refer to specific manufacturer's literature for recommendations. The following information is a general guide:

- The following parts should be renewed at each: gaskets, rubber sleeves, and seals. Adequate quantities should be maintained.
- The following parts have a reasonably predictable service life and require replacement at predictable periods: fuel injectors, pumps, governors, and valves. A one-year supply should be maintained.
- The following parts have a normally long life and, if failure occurs, could disable the engine for a long period of time: cylinder head, cylinder liner, piston and connecting rod, gear and chain drive parts, and oil pressure pump. One item of each part for an engine should be available.

**12.5 PARTS SALVAGE.** Certain parts may be replaced prior to their failure due to a preventive maintenance program. It may be possible to restore these parts to specified tolerances. Refer to specific manufacturer's literature for recommendations and instructions. The following information is a general guide:

- Worn pump shafts and cylinder liners may be built up and machined to specified dimensions.
- Grooves in pistons may be machined and I oversize rings specified for use.
- Press-fitted bushings and bearings may loosen. The related body part may be machined to a new dimension and oversize bushings and bearings fitted.
- Worn journals on crankshafts and camshafts may be built up and machined to specified dimensions.

**13. GAS TURBINE ENGINES.** The following provides a general description of gas turbine engines used for power generation. For generating electric power, a turboshaft (shaft turbine) engine is used (see fig 3-19). In a turboshaft engine, the turbine provides power in excess of that required to drive the engine compressor. The excess power is applied as rotary driving torque available at an output shaft. The power to drive the output shaft is extracted from the same turbine that drives the compressor. The turbine is usually connected through a gearbox to the generator. The gearbox is used for speed reduction.

## 14. GAS TURBINE ENGINE CLASSIFICATIONS.

**14.1 PRESSURE AND STAGES.** Gas-turbine engines used for auxiliary power generator sets are classified as high-pressure-turbine (HPT) or low-pressure turbine (LPT) types. Additionally, the engines are classified by the number of stages employed in the turbine design. In general, the more stages used in the design, the greater the engine torque. All of the turbine rotor stages in the multi-stage turbine are connected to a common shaft.

**14.2 POWER REQUIREMENT.** For a specified prime mover power requirement, the engine design can be either a single-stage, large diameter turbine or an equivalent small diameter multi-stage turbine.

**14.3 SIMPLE CYCLE**. Most engines are designed to use natural gas and/or liquid fuel similar to kerosene. These are called simple-cycle engines.

**14.4 COMPRESSOR AND COMBUSTOR**. Most engines have an axial flow compressor and a cannular or annular combustion section (combustor).

## 15. PRINCIPLES OF OPERATION.

**15.1 COMPONENTS.** A typical gas turbine engine consists of a compressor, combustor and turbine (see fig 3-20).

**15.1.1 THE COMPRESSOR IS DRIVEN** by the turbine through a common shaft. Air enters the compressor via an inlet duct. The compressor increases the air pressure and reduces the air volume as it pumps air to the combustor and through the engine.

**15.1.2 FUEL (LIQUID AND/OR NATURAL GAS)** is delivered to the combustor by a fuel system consisting of a manifold, tubes, and nozzles. Electrical igniters in the combustor provide a spark to ignite the fuel/air mixture for engine start-up. The igniters are deactivated after start-up has been accomplished. Hot combustion gases are expelled through the turbine.

**15.1.3 THE TURBINE EXTRACTS** energy from the hot gases, converting it to rotary power which drives the compressor and any load, such as a generator. Exhaust gases are vented via ductwork to the atmosphere.

**15.1.4 THE AIR INTAKE FOR A GAS TURBINE ENGINE** usually consists of a plenum chamber with a screened inlet duct opening. The plenum chamber and duct are engine emplacement features that may vary at connected by tubes to allow flame propagation during ignition and operation. The filters remove debris and other material that would otherwise be drawn into the engine compressor causing damage. Usually the lowest part of the plenum is equipped with a drain for removal of moisture.

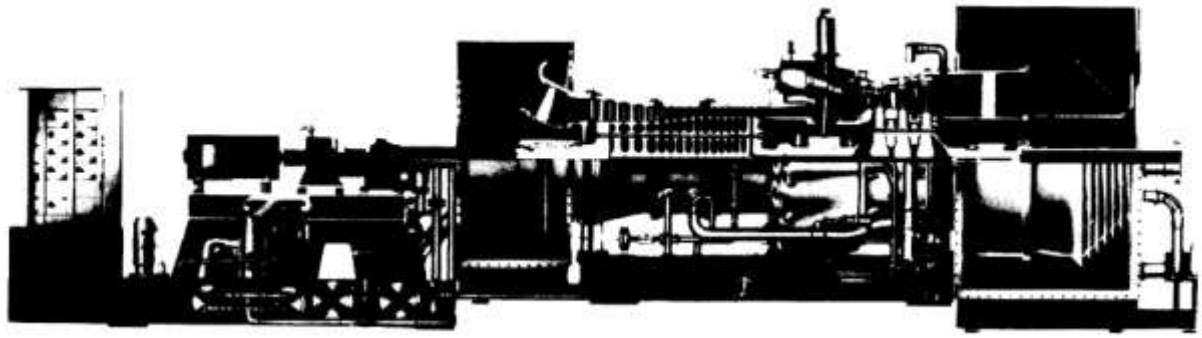


Figure 3-19

Typical gas turbine engine for driving electric power generator.

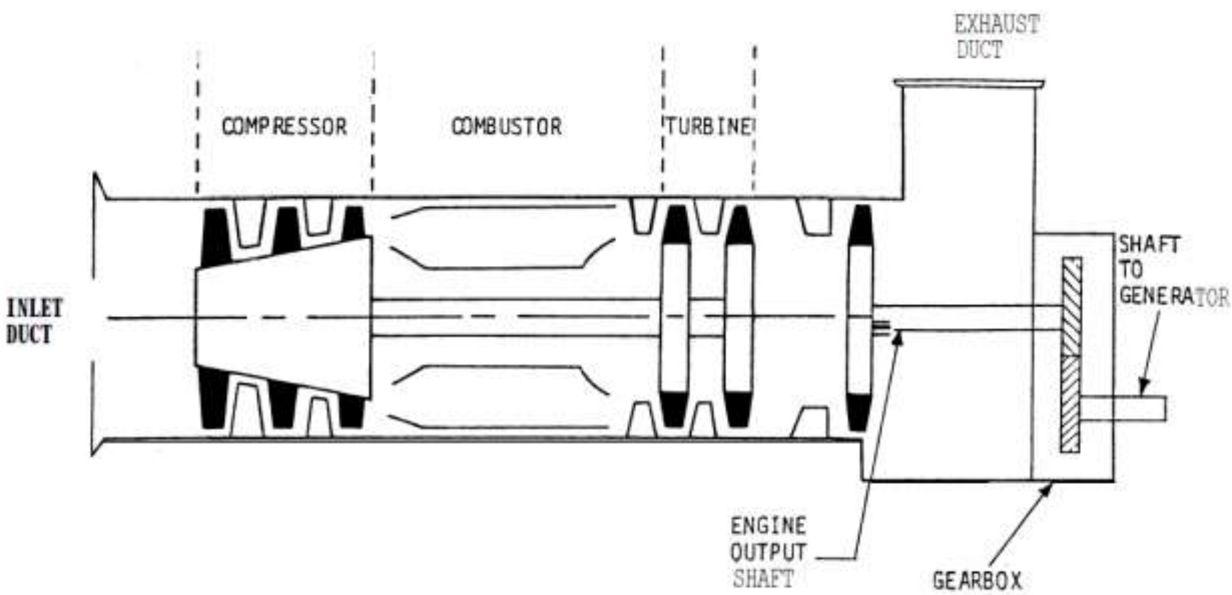



Figure 3-20

Gas turbine engine, turboshaft

**15.2 SEQUENCE OF EVENTS.** Combustion causes an increase in gas temperature proportionate to the amount of fuel being injected, a moderate increase in velocity, and a negligible decrease in pressure. Approximately 25 percent of the compressor's total air flow is used for combustion at an air/fuel ratio of about 15:l. The remaining 75 percent of compressor air output is fed to the combustor and to cool combustor liners for cooling combustion gases before they enter the turbine. (1) The sequence of events during turbine engine start-up and operation is as follows:

**15.2.1 AIR IS DRAWN INTO THE COMPRESSOR** by rotating the engine. Rotation is accomplished by the engine starter. The engine is rotated to the speed at which it becomes self-sustaining.

**15.2.2 AS THE ENGINE SHAFT IS ROTATED** and accelerated by the starter, fuel is fed to the combustor. When the air pressure is high enough, the air/fuel mixture is ignited by an electrical spark.

**15.2.3 THE ELECTRICAL SPARK** is deactivated after ignition occurs. Since the air/fuel mixture is continuously fed to the combustor by the turbine and compressor, and since there is a flame in the combustor after ignition, engine operation is self-sustaining.

**15.2.4 ROTATION OF THE ENGINE** by the starter is necessary after combustion takes place to help accelerate the engine to rated speed. Once the engine speed has increased to approximately 60 percent of rated speed, the starter is deactivated.

**15.2.5 GAS TURBINE ENGINES** have dual-fuel capability since they may use either liquid or gaseous fuel. Generating units with these engines are reliable and virtually free of vibration.

**15.3 TYPES OF COMBUSTORS.** Combustors for gas turbine engines for generators are either cannular or annular-type with newer engines usually having an annular combustor. The annular-type engine is described in this manual. See figure 3-21 for details. The annular combustor consists of a continuous circular inner and outer casing or shell; the space between the casings is open. The cannular combustor consists of inner and outer combustion casings mounted coaxially around the engine compressor/rotor shaft. A cluster of burner cans are located between the two casings. The cans are interconnected by tubes to allow flame propagation during ignition and operation.

## 16. GAS TURBINE FUEL SYSTEM.

**16.1 SYSTEM COMPONENTS.** The system provides the engine with the proper amount of fuel to sustain operation. System components include filters, a fuel manifold, fuel tubes, and nozzles. Off-engine components include the fuel control equipment and a supply system.

**16.1.1 THE SEQUENCE OF EVENTS** during turbine engine start-up and operation is as follows:

(a) Air is drawn into the compressor by rotating the engine. Rotation is accomplished by the engine starter. The engine is rotated to the speed at which it becomes self-sustaining.

(b) As the engine shaft is rotated and accelerated by the starter, fuel is fed to the combustor. When the air pressure is high enough, the air/fuel mixture is ignited by an electrical spark.

(c) The electrical spark is deactivated after ignition occurs. Since the air/fuel mixture is continuously fed to the combustor by the turbine and compressor, and since there is a flame in the combustor after ignition, engine operation is self-sustaining.

(d) Rotation of the engine by the starter is necessary after combustion takes place to help accelerate the engine to rated speed. Once the engine speed has increased to approximately 60 percent of rated speed, the starter is deactivated.

(e) Gas turbine engines have dual-fuel capability since they may use either liquid or gaseous fuel. Generating units with these engines are reliable and virtually free of vibration.

**16.1.2 TYPES OF COMBUSTORS.** Combustors for gas turbine engines for generators are either cannular or annular-type with newer engines usually having an annular combustor. The annular-type engine is described in this manual. See figure 3-21 for details. The annular combustor consists of a continuous circular inner and outer casing or shell; the space between the casings is open. The cannular combustor consists of inner and outer combustion casings mounted coaxially around the engine compressor/rotor shaft. A cluster of burner cans are located between the two casings.

**16.2 FUEL.** Fuel (liquid and/or natural gas) enters the tubular fuel manifold ring via the supply system. The fuel tubes direct the fuel from the manifold to the fuel nozzles which are mounted in the fuel swirlers (see fig 3-22 and 3-23). Compressor discharge air flows radially inward through the primary swirler in the combustion liner, which rotates the air circumferentially and mixes it with the fuel. Air entering radially inward through the secondary swirler is caused to rotate in the opposite direction. As the two counter-rotating mixtures join, the fuel mixes completely with the air. This process promotes complete mixing of the fuel and air and, therefore, more complete burning of the mixture resulting in less smoke emission and more uniform temperature distribution within the combustor.

**16.3 IGNITION**. Ignition is accomplished by one or two igniter plugs. At ignition, the igniters are activated and fuel is injected into the swirlers. After ignition, the igniters are deactivated.

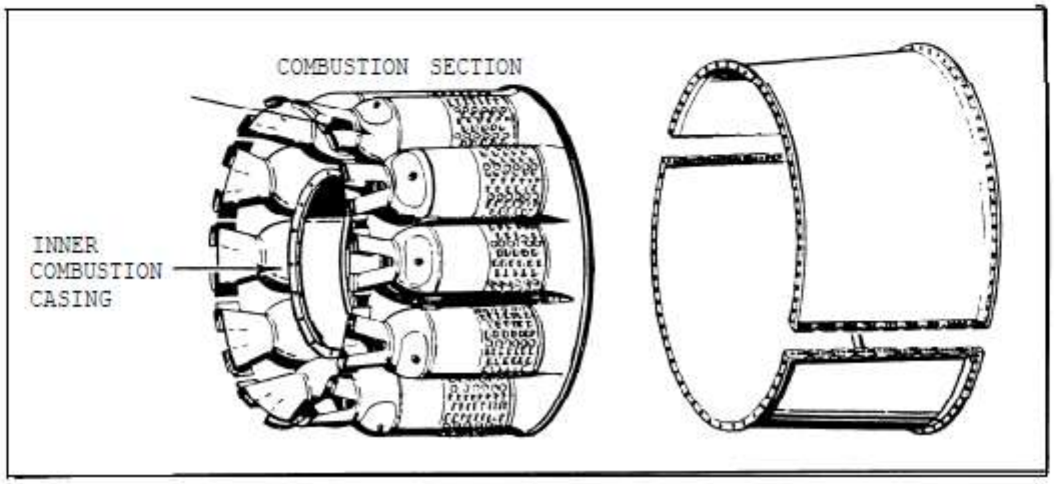
## 17. GAS TURBINE COOLING SYSTEM.

**17.1 APPROXIMATELY 25 PERCENT** of the air entering a combustor is mixed with fuel and burned. The remaining air is mixed with the products of combustion to reduce the temperature of gases entering the turbine to a safe operating level. Cooling is accomplished by engine airflow.

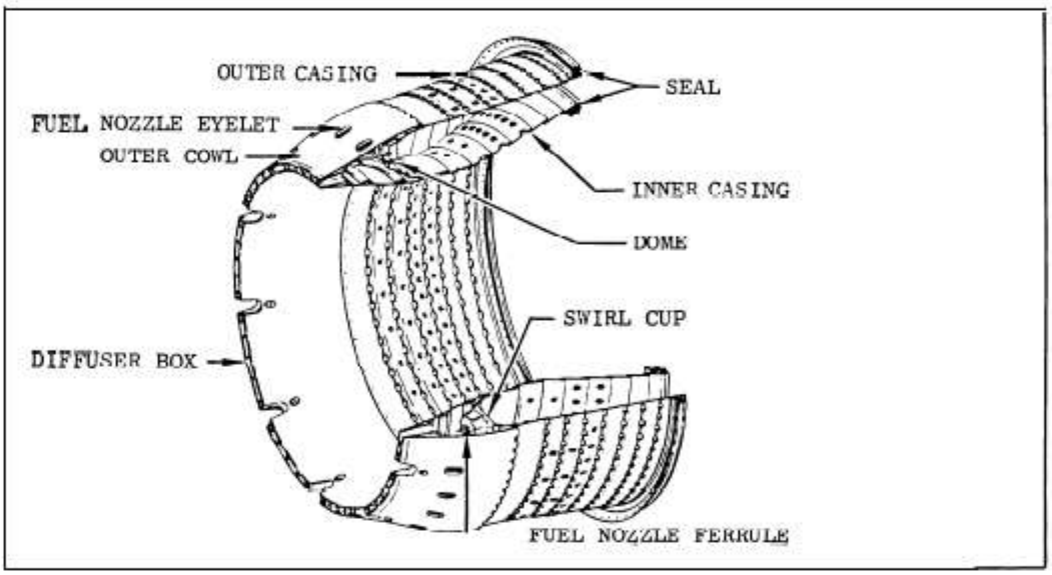
**17.2 THREE FORMS OF AIR COOLING** of the vanes and blades are used, either separately or in combinations. The types of cooling are convection, impingement, and film (see fig 3-24).

**17.2.1 CONVECTION.** For convection cooling, air flows inside the vanes or blades through serpentine paths and exits through the blade tip or holes in the trailing edge. This form of cooling is used in the area of lower gas temperature (see fig 3-25).

**17.2.2 IMPINGEMENT.** Impingement cooling is a form of convection cooling, accomplished by directing cooling air against the inside surface of the airfoil through small internal high velocity air jets. Cooling is concentrated at critical sections, such as leading edges of vanes and blades (see fig 3-26).




CANNULAR COMBUSTOR COMBUSTION OUTER CASING




ANNULAR COMBUSTOR

Figure 3-21

Typical types of combustors

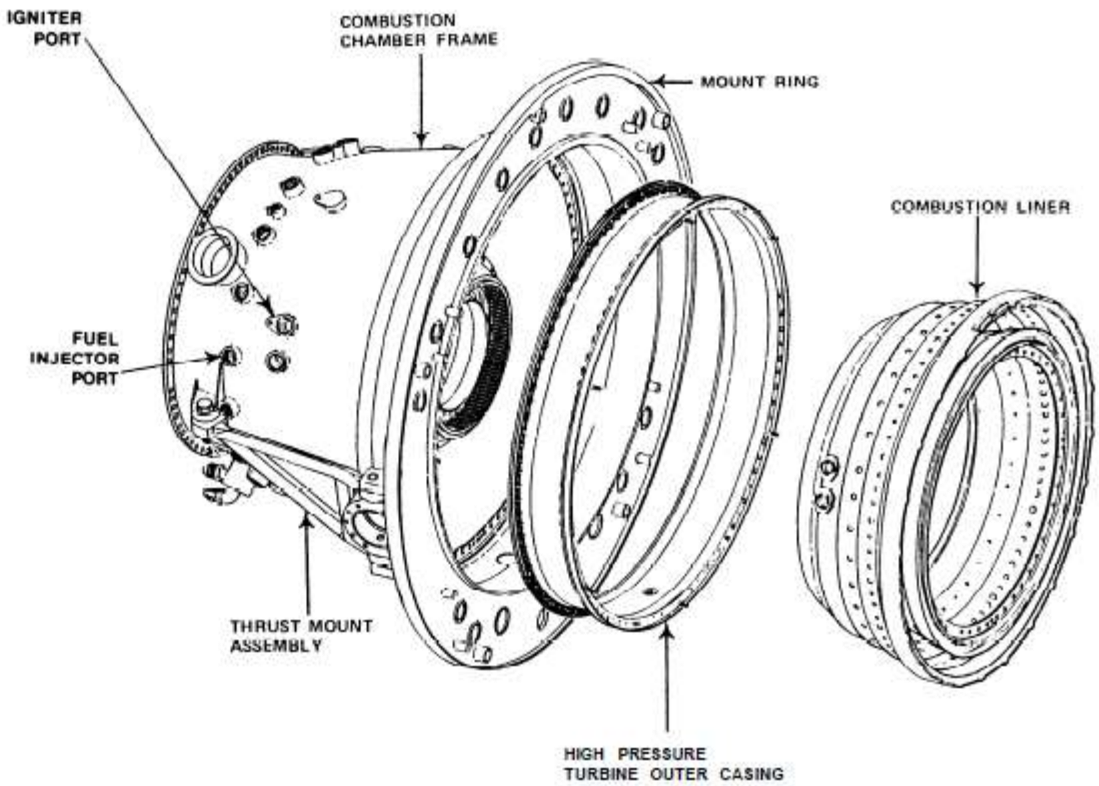



Figure 3—22

Engine combustion section

**17.2.3 FILM.** Film cooling is a process whereby a layer of cooling air is maintained between high temperature gases and the external surfaces of the turbine blades and vanes. In general, film cooling is the most effective type.

## 18. LUBRICATION SYSTEM.

**18.1 THE LUBRICATION SYSTEM** for a gas turbine engine is usually self-contained with the engine and supplies oil for lubrication and cooling during engine operation (see fig 3-27). Engine bearings in the compressor, combustor, and turbine areas (identified as areas A, B, and C, respectively) are supplied by the system. System pressure is approximately 75 psi and is usually maintained by a supply and scavenge pump. Most systems include a heat exchanger to cool the oil and an oil supply tank.

**18.2 ON-ENGINE COMPONENTS** usually include lubrication supply and scavenge piping, a supply temperature RTD sensor (resistance temperature detector), and chip detectors at A, B, and/or C oil collection sumps. Nozzles are provided for oil distribution to bearings. Off-engine components include flexible oil lines between on-engine and off-engine components, oil cooler, oil tank, lubrication supply differential pressure sensor, and lubrication pump. Oil is supplied by jet or spray to bearings in other areas via tubes. The engine starter is usually located in an accessory gearbox.

**18.2.1 A-SUMP.** Oil for A- sump components is usually piped from a gearbox into the sump. Internal passages and manifolding carry the oil to the A-sump housing. A double-headed nozzle supplies oil to the forward bearing and the undercooled carbon seal runner for the bearing. The second bearing is lubricated through oil nozzles mounted on a power take-off housing. Oil is supplied to the rear bearings through jets on the forward and aft sides of the bearing. The carbon seal runner for the bearing is cooled by oil which has lubricated the power takeoff unit and the compressor forward shaft, and is then sprayed outward through holes in the shaft. This oil is then passed through holes at the seal runner where an oil slinger moves it away from the carbon seal.

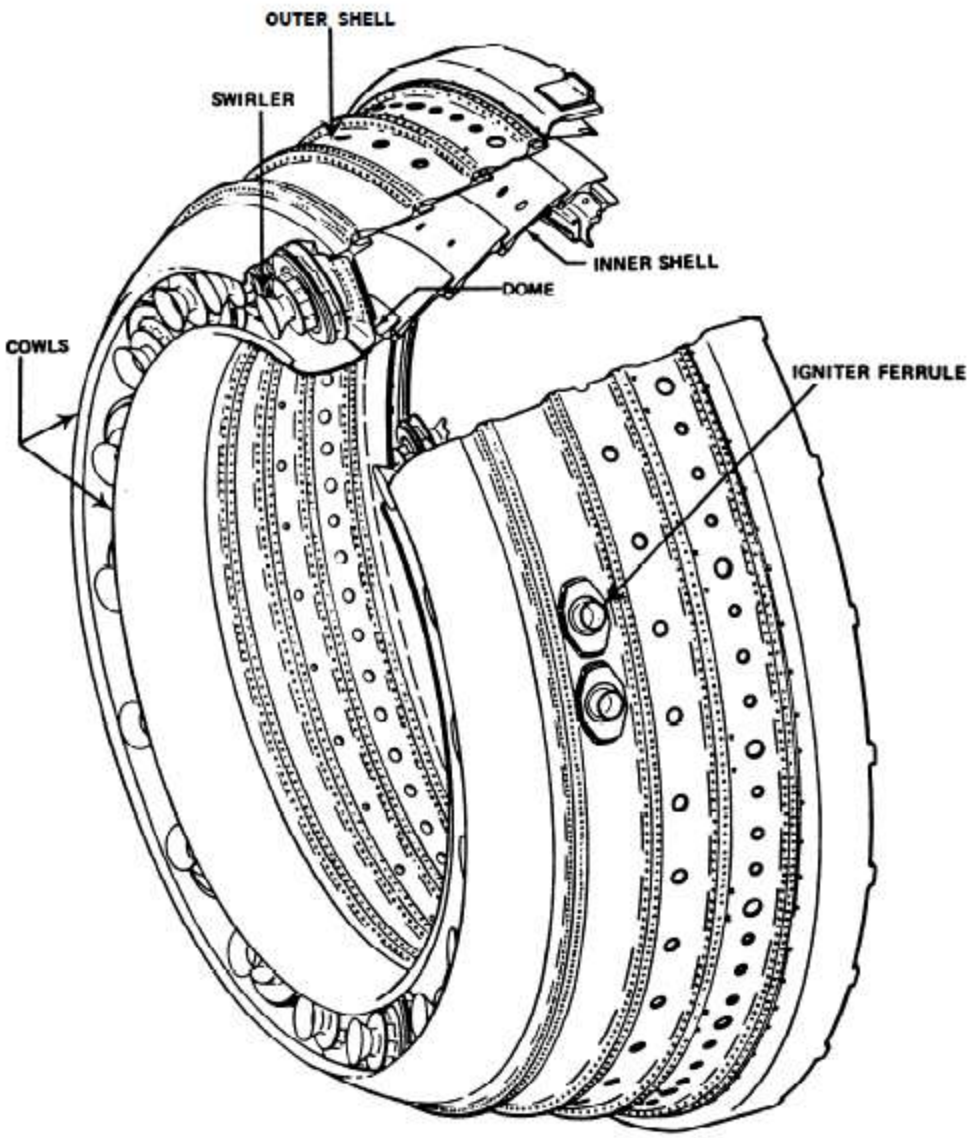



Figure 3-23

Engine combustion liner

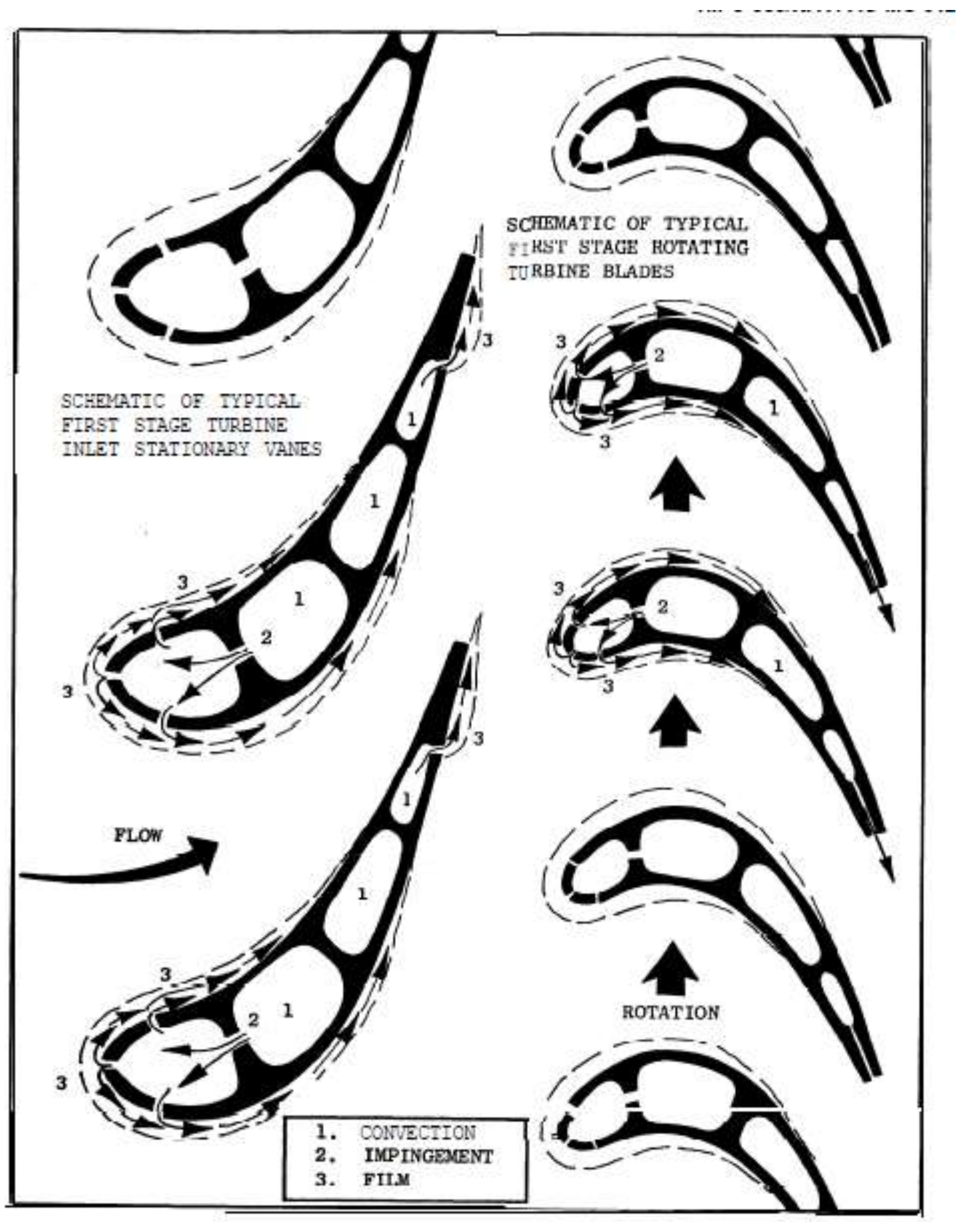



Figure 3-24

Air cooling modes of turbine vanes and blades

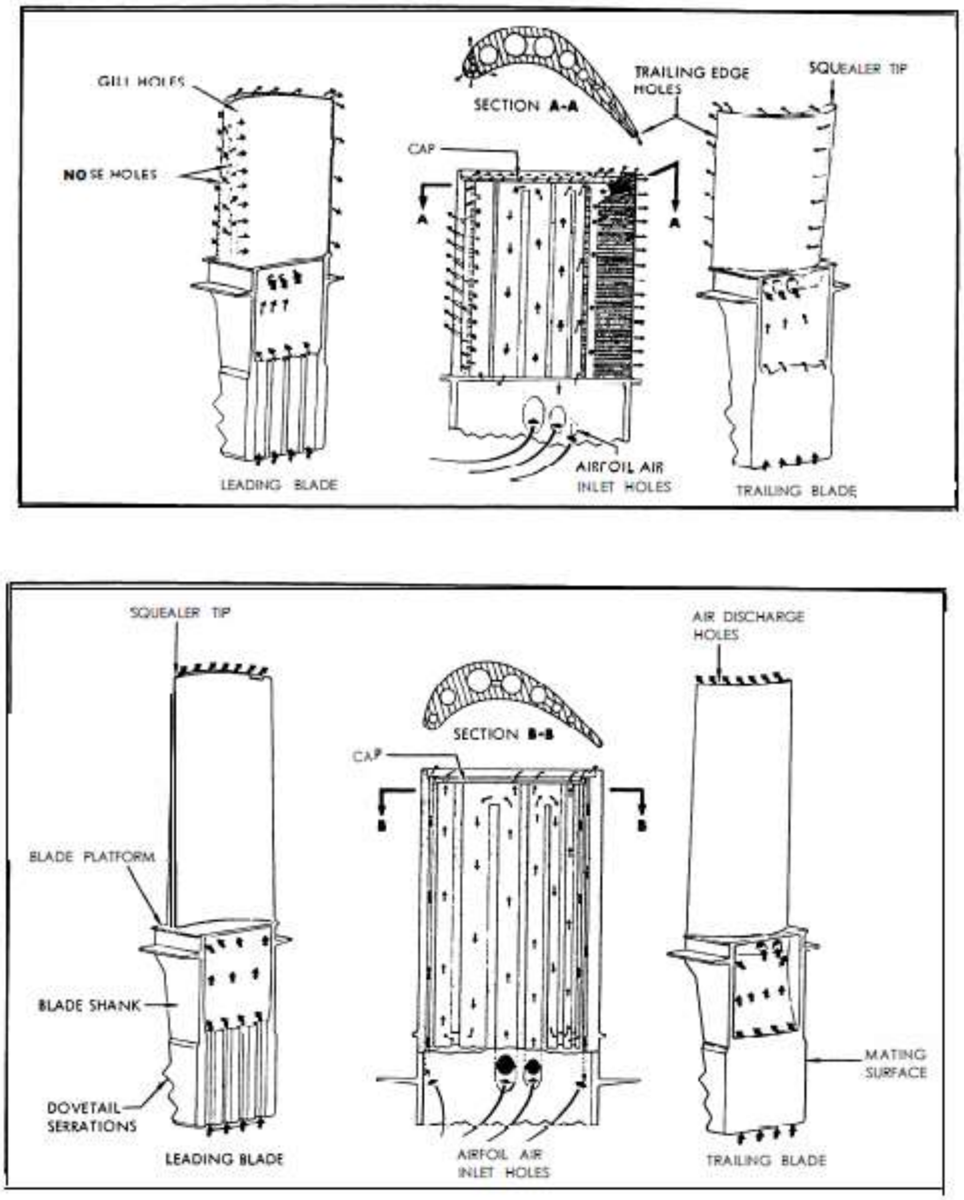



Figure 3-25

Turbine blade cooling air flow

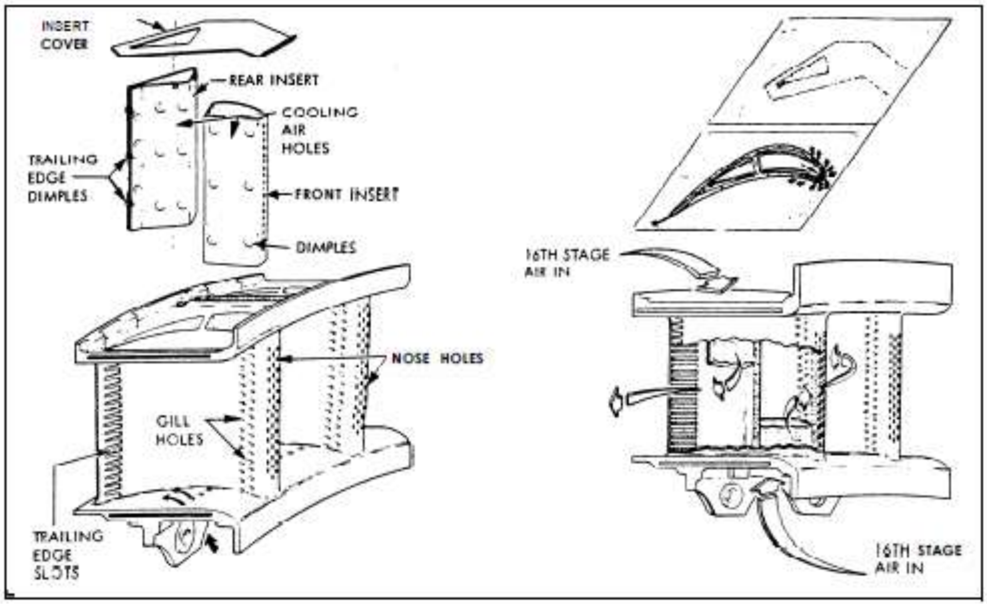



Figure 3-26

Turbine vane cooling air flow

**18.2.2 B-SUMP.** Oil enters the B-sump via a frame strut and is directed through tubing in the housing to the mid-engine bearing oil nozzles. Each nozzle has two jets. One jet supplies oil to the bearing and the other jet supplies oil to the carbon seal runner for the bearing.

**18.2.3 C-SUMP.** Oil enters the C-sump through a feed tube and is diverted internally through manifolding and tubing to the oil nozzles. In many engines, the rearmost nozzle has two heads with two jets in each head. One set of jets sprays oil on the bearing. The other set sprays oil on the bearing locknut which causes the oil to spray on the rear wall of the C-sump cover and vent collector to cool it and reduce coking. The adjacent bearing oil nozzle also usually has two heads with two jets in each. Two jets direct oil onto the bearing and the others direct oil to the carbon seal runner for the bearing

**18.2.4 SCAVENGING**. Scavenging is accomplished by a multi-element lubrication and scavenge pump. One element is used for pumping. The other elements are used for forward and aft scavenging of the B-sump and C-sump. Oil in the A-sump drains by gravity into the accessory gearbox.

**18.2.5 VENTING.** Some lubrication systems are vented. To maintain high differential pressure across the carbon seals to prevent oil leakage, a high sump vent capacity is required. The A and C sumps vent through the engine output shaft and vent collector to ambient. The B-sump vents to the turbine exhaust gas stream.

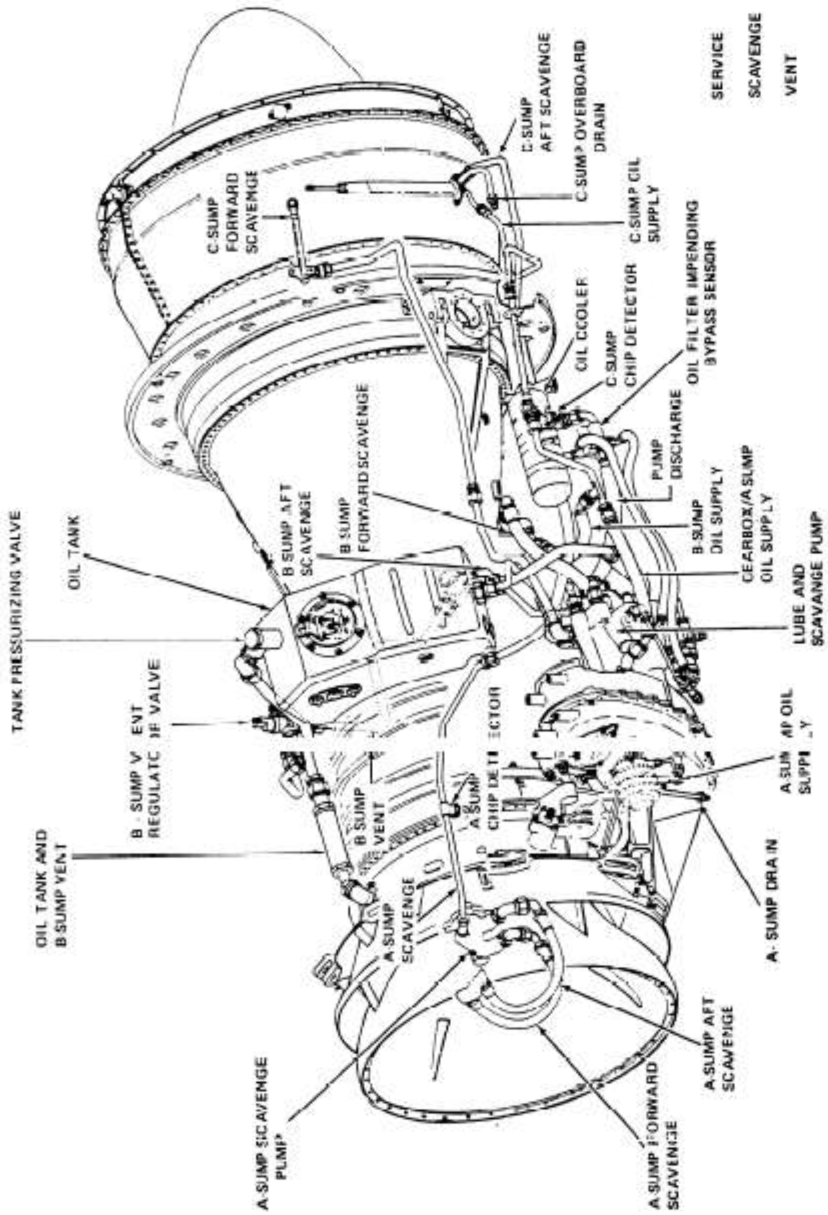



Figure 3-27

Lubrication system for gas turbine

**19. STARTING SYSTEM.** Gas turbine engine starters must be capable of rotating an engine up to a speed-at which it becomes self-sustaining. The starter must provide sufficient torque to accelerate the engine from a standstill to a self-sustaining speed within a specified time. Although it must continue to assist the engine in accelerating up to a predetermined speed.

**19.1 ELECTRIC MOTOR.** An electric starter motor is usually used for a gas turbine engine in service as an auxiliary generator prime mover. The starter rotates the engine compressor shaft via the gear train in the accessory gearbox. In most installations the starter can be energized either automatically or manually.

**19.2 FUEL.** As the engine is accelerated by the starter, fuel is supplied when a specified rotational speed is attained. When this speed is attained, the compressor and engine-driven fuel pump will deliver sufficient air and fuel, respectively to the combustion chamber to sustain satisfactory combustion.

**19.3 IGNITION SYSTEM.** An ignition system, consistingof an ignition exciter, igniter plug lead assemblies, and igniter plugs, is required. Fuel ignition is ensured by one or two igniter plugs connected to the exciter by the separate igniter leads. The plugs are located in the combustion chamber. Each plug consists of center and outer electrodes with a semiconductor surface coating at the tip between the two electrodes. The semiconductor material is used as a shunt to aid in ionizing the air gap between the two electrodes so that the plugs will fire. An air shroud covers the end of the plug immersed in the air stream for cooling.

**19.4 SPECIALIZED SYSTEM**. Starting systems are highly specialized and are usually applicable to a given installation or site. Refer to supplier's on-site technical literature for details.

## 20. GOVERNOR/SPEED CONTROL.

**20.1 ENGINE OPERATION.** The engine is started by an external power source. Once the engine reaches idle speed, it is self-sustaining. All it needs is adequate supplies of air and fuel. Combustion gas drives the turbine which is mounted on a common shaft with the compressor. The compressor draws in the air for combustion and also drives the gearbox gear train. About two-thirds of the power derived from combustion is required to sustain combustion. The remaining power is available for work purposes and drives the output shaft.

**20.2 SPEED SIGNAL.** An engine speed signal, generated by magnetic pickups (speed transducers) in the gearbox, provides electrical signals that are proportional to engine speed. The signal causes a dc voltage to be generated.

**20.3 THERMOCOUPLES.** Thermocouples sense the turbine discharge/inlet total temperature. The electrical temperature sensing signal is an average of the operating temperature profile.

**20.4 PRESSURE SENSING.** Sensing of compressor discharge static pressure and turbine discharge pressure is also required for engine speed control. These pressures are combined to produce an electrical signal equal to pressure ratio.

**20.5 COMPUTER.** The three signals (speed, temperature, and pressure ratio) are summed in an acceleration/deceleration computer. Computer output functions with a governor to meter fuel required for engine operation. If required, a signal derived from a tachometer can be used to determine a rate-of- change feedback signal.

**21. COMPRESSOR.** The function of the compressor is to raise the pressure and reduce the volume of the air as it pumps it through the engine. An axial flow or centrifugal flow compressor is used. Most engines use a multistage, axial flow compressor such as described herein. The axial flow consists of two major subassemblies: the rotor assembly and the stator assembly. Axial flow compressor efficiency is better than centrifugal flow compressor efficiency. Centrifugal flow compressors were first used in early design gas turbine engines. The main component is an impeller which is mounted on a common shaft with the turbine. These compressors are generally used with smaller engines and have a fairly low pressure ratio. The design has lower efficiency than the axial-flow design but is less expensive to manufacture.

**22. GAS TURBINE SERVICE PRACTICES.**

**22.1 MAINTENANCE PROGRAM.** Service practices for gas turbine engines consist of a complete maintenance program that is built around records and observation. The program is described in the manufacturer's literature furnished with each engine. It includes appropriate analysis of these records.

**22.2 RECORD KEEPING**. Engine log sheets are an important part of record keeping. The sheets must be developed to suit individual applications (i.e., auxiliary use) and related instrumentation.

**22.3 LOG SHEET DATA**. Log sheets should include engine starts and stops, fuel and lubrication oil consumption, and a record of the following:

- Hours since last oil change.
- Hours since first put in service or last overhaul.
- Total hours on engine.

**22.4 OIL ANALYSIS PROGRAM.** Use of a Spectrometric Oil Analysis Program is recommended to determine the internal condition of the engine's oil-wetted (wear metal) components, such as bearings, gears, and lubrication pump.

**22.4.1 THE PROGRAM** should be used as a supplement to the regular maintenance procedure of chip detection and filter inspection. Normal wear causes microscopic metal particles (smaller than one micron) to mix with the lubricating oil and remain in suspension. Samples of oil taken from the engine after a shutdown will contain varying amounts of wear-metal particles.

**22.4.2 OIL SAMPLES SHOULD** be removed from the engine at the time intervals specified by the engine manufacturer. A sample should always be taken from the same location on the engine (this may vary from each engine). Refer to manufacturer's literature.

**22.4.2.1 METAL CONTENT**. Evaluation of the oil's wear-metal content is very important. The quantity of wear-metal in the sample as well as type (iron or steel, silver, chromium, nickel, etc.) must be evaluated and recorded.

**22.4.2.2 FAILURE FORECAST**. Evaluation records are intended as an aid in forecasting what components are in danger of failing. Contamination of the oil sample must be prevented to avoid false indication of engine internal conditions. ,

**22.5. INDUSTRIAL PRACTICES**. Use recognized industrial practices as the general guide for engine servicing. Service information is provided in manufacturer's literature.

**22.6 REFERENCE LITERATURE.** The engine user should refer to manufacturer's literature for specific information on individual units.