6.1.3
ENGINES

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ENGINE SELECTION AND APPLICATION

The internal combustion engine is used extensively as a driver for centrifugal and displacement pumps. Depending on the application, the engine fuel may be gasoline, natural gas, liquid petroleum gas (LPG), sewage gas, or diesel fuel. It may be either liquid- or air-cooled.

Basic Design Variations The basic design of the engine may vary. The cylinder block construction is vertical or horizontal, in-line or V-type. The number of cylinders ranges from 1 to 20. The engine cycle is either four (one power stroke in two revolutions of the crankshaft) or two (one power stroke in one revolution of the crankshaft). The combustion chamber and cylinder head design are classed as L-head (valves in the cylinder block) or valve-in head. In the diesel engine, the combustion chamber may be of the precombustion chamber design, where an ante chamber is used to initiate combustion, or of the direct injection design, where the fuel is injected directly into the cylinder. The piston design action may be vertical, horizontal, at an angle as in the V-type engine, or opposed piston (two pistons operating in the same cylinder).

Power Ratings The power range of engines in current production, depending on displacement, number of cylinders, and speed, is as follows:

1. Air-cooled gasoline, natural gas, and diesel: 1.0 to 75 hp (0.75 to 56 kW)
2. Liquid-cooled gasoline: 10 to 300 hp (75 to 224 kW)
3. Liquid-cooled natural gas, LPG, and sewage gas: 10 to 15,000 hp (75 to 11,200 kW)
4. Liquid-cooled diesel: 10 to 50,000 hp (75 to 37,300 kW)
5. Dual fuel, natural gas, LPG, and diesel: 150 to 25,000 hp (112 to 18,700 kW)

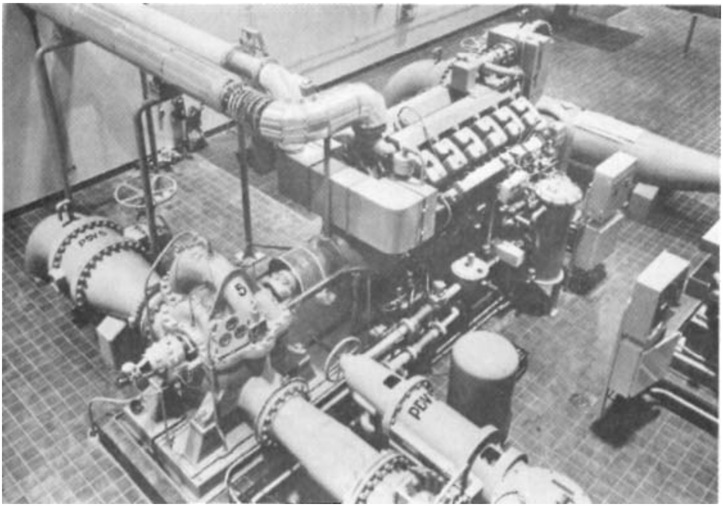

FIGURE 1 Natural gas engine driving a horizontal water pump for Winnipeg, Canada, water utility (Waukesha Motor)

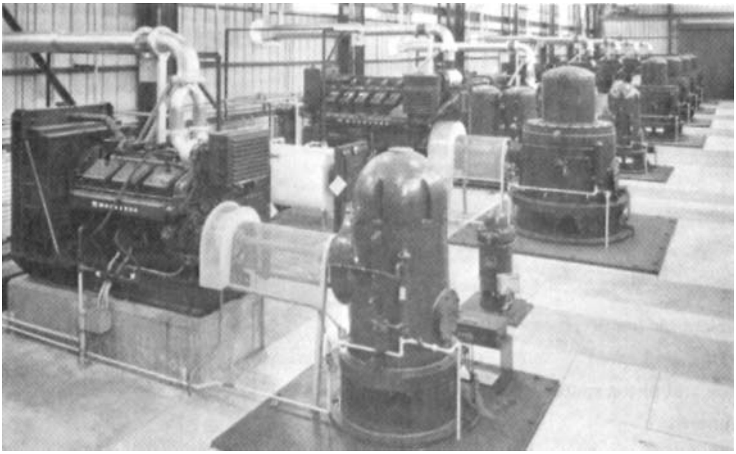

FIGURE 2 Diesel engine driving pumps for flood-control station in Seattle (Waukesha Motor)

Typical engine driver applications are represented in Figures 1 and 2.

The rating of the internal combustion engine is the most important consideration in making the proper selection. The general practice is to rate engines according to the severity of the duty to be performed. The most common rating classifications are maximum, standby or intermittent, and continuous.

The maximum output is based on dynamometer tests that are corrected to standard atmospheric conditions for temperature and barometric pressure. In applications, this power rating is reduced by accessories such as cooling fans, air cleaners, and starting systems.

Standby, or intermittent, and continuous ratings are arrived at by applying a percentage factor to the net maximum power rating. For example, 75 to 80% is used for continuous and 90% for intermittent.

Duty cycle is a term used to describe the load pattern imposed on the engine. If the load factor (ratio of average load to maximum capabilities) is low, we call the duty cycle "light," but if it is high, we classify the cycle "heavy." Continuous, or heavy-duty, service is generally considered to be 24 h/day, with little variation in load or speed. Intermittent service is classified as duty where an engine is called upon to operate in emergencies or at reduced loads at frequent intervals.

In analyzing power problems when selecting a proper engine, certain terms are used in the industry:

DISPLACEMENT The displacement in cubic inches (cubic centimeters) of an engine cylinder is

In USCS units, $D = \text{bore (in}^2) \times 0.7854 \times \text{stroke (in)} \times \text{no. of cylinders}$

In SI units $D = \text{bore (cm}^2) \times 0.7854 \times \text{stroke (cm)} \times \text{no. of cylinders}$

Torque The twisting effort of the engine in pound-feet (Newton-meters) is

In USCS units $$T = 5252 \times \frac{\text{bhp}}{\text{rpm}}$$

In SI units $$T = 9545 \times \frac{\text{bkW}}{\text{rpm}}$$

ENGINE POWER This is a measure of the theoretical characteristics of an engine. Brake horsepower (bkw) is the measurable power after the deduction for frictional losses:

In USCS units $$\text{bhp} = T \times \frac{\text{rpm}}{5252}$$

In SI units $$\text{bkW} = T \times \frac{\text{rpm}}{9545}$$

BRAKE MEAN EFFECTIVE PRESSURE The average cylinder pressure to give a resultant torque at the flywheel in pounds per square inch (kilopascals)

In USCS units $$\text{bmep} = \frac{792{,}000 \times \text{bhp}}{\text{rpm} \times D} \text{ (four-cycle)}$$

$$\text{bmep} = \frac{396{,}000 \times \text{bhp}}{\text{rpm} \times D} \text{ (two cycle)}$$

In SI units $$\text{bmep} = \frac{120 \times 10^6 \times \text{bkW}}{\text{rpm} \times D} \text{ (four-cycle)}$$

$$\text{bmep} = \frac{60 \times 10^6 \times \text{bkW}}{\text{rpm} \times D} \text{ (two cycle)}$$

PISTON SPEED At a given speed, the average velocity of piston in feet per minute (centimeters per minute) is

In USCS units $$\text{Piston speed} = \text{stroke (in)} \times 2 \times \frac{\text{rpm}}{12}$$

In SI units $$\text{Piston speed} = \text{stroke (cm)} \times 2 \times \frac{\text{rpm}}{6000}$$

In selecting an engine for a particular application, the following variables should be considered:

- Altitude
- Ambient air temperature

- Rotation and speed
- Bmep and piston speed
- Maintenance
- Type of fuel
- Operating atmosphere (dust and dirt)
- Vibrations and torsionals
- Engine pollutants

The observed power is that produced by an engine at the existing altitude and temperature. All engine manufacturers publish power ratings corrected to certain conditions; for conditions other than these, it is necessary to correct by applying a percentage factor for altitude and temperature. Generally this is $3\frac{1}{2}\%$ per thousand feet (305 m) above sea level and 1% for every 10°F (5.6°C) above 60°F (50.4°C). In a turbocharged engine, there is no established standard and the engine manufacturer should be consulted.

The basic rotation of engines in current production is counterclockwise when viewed from the flywheel end of the engine, although many of the larger engines are available in both counterclockwise and clockwise rotation. The speed of the engine is generally fixed by the equipment being driven. Through the use of speed-increasing or -reducing gear boxes, the proper engine for a given application may be selected. A gear box may also be used to correct a rotation problem.

Speed ranges for engines generally fall into three categories:

- High—above 1500 rpm
- Medium—700 to 1500 rpm
- Low—below 700 rpm

High-speed engines generally offer weight and size advantages as well as cost savings and thus are used for standby applications. On the other hand, medium- or low-speed engines, although heavier and larger, offer a gain in service life and lower maintenance costs.

The speed flexibility of an engine drive is important when the engine is to be used to drive a pump that must move variable quantities of liquid. The engine speed may be changed very simply either manually or through the use of liquid or pressure controls.

Bmep is generally a measure of load, and piston speed a measure of potential wear and maintenance. Although the introduction of the turbocharged and intercooled engine has somewhat changed the consideration given these factors, it is still important to consider them in selecting engines where long life is a factor.

Maintenance of engines has been considered by some as objectionable and more costly than electric power. A recent innovation of engine manufacturers, in the form of a service contract for installations where trained personnel are not available or desirable for economic reasons, can eliminate these objections and costs. The complete maintenance of the engine is done on a fixed-fee basis for a designated period of time.

The exhaust gases of spark ignition and compression ignition (diesel) engines contain pollutants that for many engine applications are increasingly the subject of legislation restricting the quantity of pollutants the engine can emit. Examples of pollutants are carbon monoxide (CO), oxides of nitrogen (NOx), unburned hydrocarbons (HC), and, for diesels, particulates in the form of carbon soot. Pollutants can be measured on a specific basis, such as g/bhp-hr and ppm (parts per millions by volume), or on a site basis, such as lb/hr or tons/year. Engine manufacturers are designing "clean" engines that incorporate features to minimize the formation of pollutants during combustion and may include catalytic converters and particulate fibers in the exhaust system to further reduce the pollutants emitted in the exhaust gases.

The remaining conditions listed previously will be discussed in detail later.

FUEL SYSTEMS

Gasoline Gasoline is used primarily with standby pumping units. Inasmuch as the spark ignition system first introduced the internal combustion engine to power applications, gasoline was used as the primary fuel. Commercial gasoline has an average heating value of 19,000 Btu/lb (44.2 MJ/kg). It is easy to transport and handle and, unlike gaseous fuels, does not require pressure storage and regulating equipment. The starting capabilities of a gasoline engine are satisfactory, provided the engine is in good operating condition. With the high-power engine of today, refinery control can produce a fuel matched to the operating conditions.

Gasoline does have some disadvantages that are reducing its use as an engine fuel. In small-volume usage, it is safe and easily handled. In larger volumes, it becomes expensive and hazardous. Because it is not entirely stable, it will deteriorate when exposed to gums and resins in storage over a period of time. There is also the possibility of condensation of water in the fuel, which is detrimental to good operation. The danger of fire is always present because of leaks in the system. Finally, the increased production and distribution of gasoline have made it a target of increasing taxation, making it economically prohibitive in many installations.

Gas A gaseous fuel system using natural gas, LPG, or sewage gas may be a simple manually controlled system, such as a gasoline engine, or a carefully engineered automatic system. The basic gas carburetion system consists of a carburetor and pressure regulator mounted on the engine. A gas distribution system, like a water supply system, must be at some designated pressure and flow, and so a field pressure regulator is required. The characteristics of this regulator will depend upon the gas analysis, the displacement of the engine, the speed range, and local regulations. A typical schematic of a gas fuel system is shown in Figure 3. The location of the regulator is generally under the jurisdiction of the gas utility that supplies it. In most cases, a single field regulator is all that is required, but at times this can cause problems. For example, subsequent installation of gas-burning equipment used intermittently may cause gas pressure regulation not compatible with the small amount required for pilot lighting. A single regulator installed some distance from the engine could result in hard starting because the engine vacuum is not sufficient for a full gas flow. To eliminate this problem, the initial regulator is set at a higher pressure in order to give a readily available supply of fuel for all devices.

Natural gas has an average heating value of 800 to 1000 Btu/ft^3 (29.8 to 37.3 MJ/m^3). Commercial butane has a value of 2950 Btu/ft^3 (110 MJ/m^3), and propane a value of 3370 Btu/ft^3 (126 MJ/sn^3). Commercial LPG fuel, which is a mixture of butane and propane, varies in both amount and corresponding heating value.

LPG fuel is produced by mechanical and compression processes, and the methods of distribution and handling must meet regulations. Natural gas is usually supplied under moderate pressures, seldom exceeding 50 lb/in (345 kpa), whereas LPG fuel is supplied as

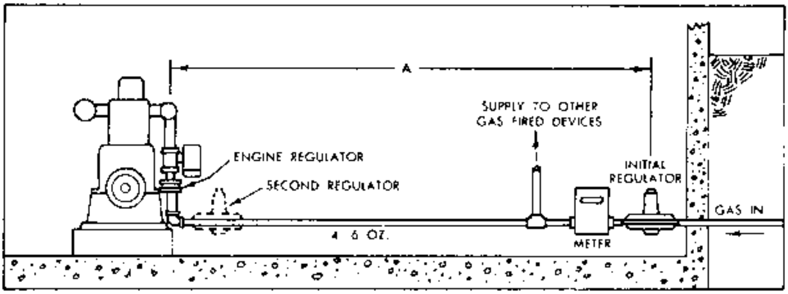

FIGURE 3 Typical natural gas fuel system (Waukesha Motor)

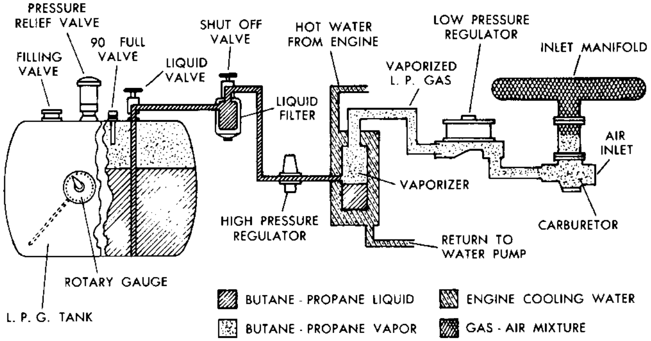

FIGURE 4 Typical LPG fuel system (Waukesha Motor)

a liquid under pressures as high as 200 lb/in^2 (1380 kPa) in warm weather. As a result, natural gas will readily mix with air and burn, whereas LPG fuel must be changed from a liquid to a vapor with the addition of heat, as shown in Figure 4.

As a natural process in the modern waste-treatment plant, sewage gas may be produced in the sewage digester. This gas has the same basic qualities as natural gas and is composed of about 65 to 70% methane. It has a heating value of 550 to 700 Btu/ft^3 (20.5 to 26.1 MJ/m^3). The same basic carburetion system used for natural gas is used. Sewage gas contains inert substances, particularly hydrogen sulfide or free sulfur, which in the presence of free moisture or moisture resulting from combustion will form sulfurous acid, which is corrosive and thus damaging to the valves, pistons, and cylinder walls of an engine. An engine can tolerate from 10 to 30 g of sulfur per 100 ft^3 (350 to 1100 g per 100 m^3). Beyond this, a filtering system to remove the sulfur and moisture is advisable.

Diesel The diesel engine over the years has been used for larger power systems. The initial cost of the system is justified to an extent by lower cost of the fuel. The better fuel economy of the diesel engine and its torque characteristics also are important factors in the selection of this fuel for many applications. Diesel fuel has one distinct advantage: it does not form the dangerous fuel vapors that other fuels do. It does require, however, a good fuel-filtering system because of contaminants in the fuel that can create problems for the precision design of the fuel-injection system.

Commercial diesel fuels are the residue that remains after the more volatile fractions of crude oil have been removed. The heating value is generally about 19,000 Btu/lb (44 MJ/kg). In the diesel engine, the fuel is injected into the cylinder at the end of the compression stroke in an atomized form. The compression stroke results in a temperature sufficient to ignite the fuel without the use of any ignition device. Although fuel systems from different engine manufacturers vary, the basic components are the same.

The larger diesel engines may be designed to operate on a dual fuel system. The engine operates on five gaseous fuels with a pilot injection of diesel fuel for ignition. In case of a loss of the gaseous fuel supply, the engine will convert to 100% diesel fuel.

Relative Performance Curves Typical performance curves comparing power, torque, and part-load fuel economy are shown in Figure 5.

COOLING SYSTEMS

Cooling is essential in all internal combustion engines because only a small portion of the total heat energy of any fuel is converted to useful energy. The remainder is dissipated into

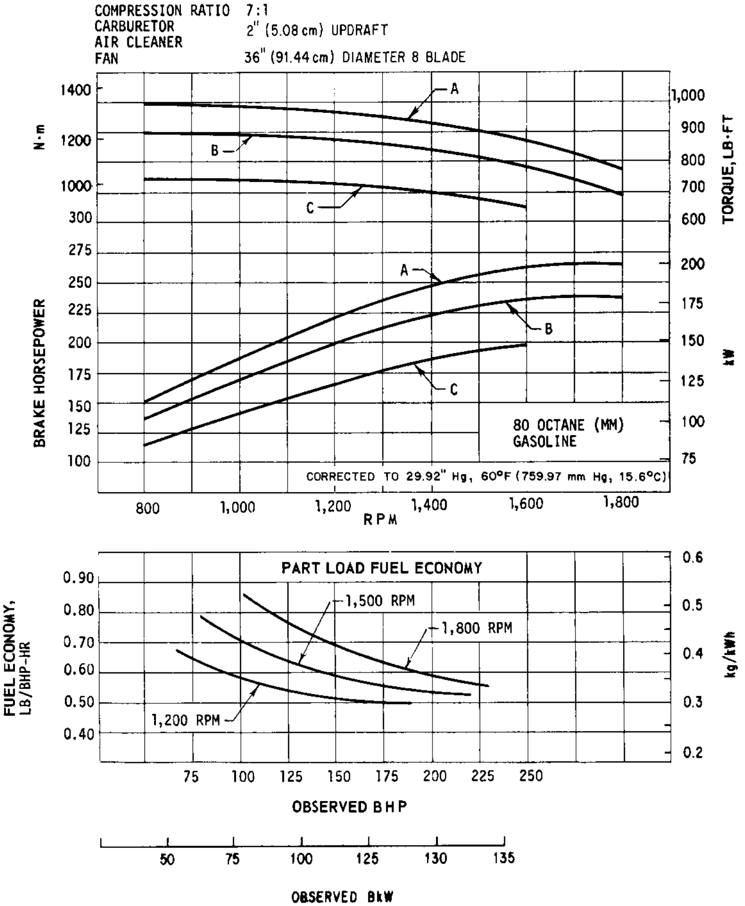

FIGURE 5A Gasoline engine performance curves: (A) maximum, (B) intermittent, (C) continuous ratings of engines with accessories (Waukesha Motor)

the coolant, exhaust, and lubricating oil and by radiation. A hypothetical heat balance is shown in Figure 6.

Specific data and recommendations on cooling requirements vary from one manufacturer to another. In general, the heat rejection to an engine cooling system will range between 30 to 60 Btu/hp · min (25 to 51 MJ/kWh) for diesel engines and up to 70 Btu/hp · min (59 MJ/kWh) for natural gas and gasoline engines. This heat must be transferred to some form of heat-exchange medium.

In designing any cooling system, certain factors must be considered:

- Additional heat from driven equipment, such as the cooling of speed-reducing or -increasing gears where the engine coolant is the medium
- Water-cooled exhaust manifolds on the engines or water-cooled exhaust turbochargers or after-coolers
- High ambient temperatures or heat from nearby equipment

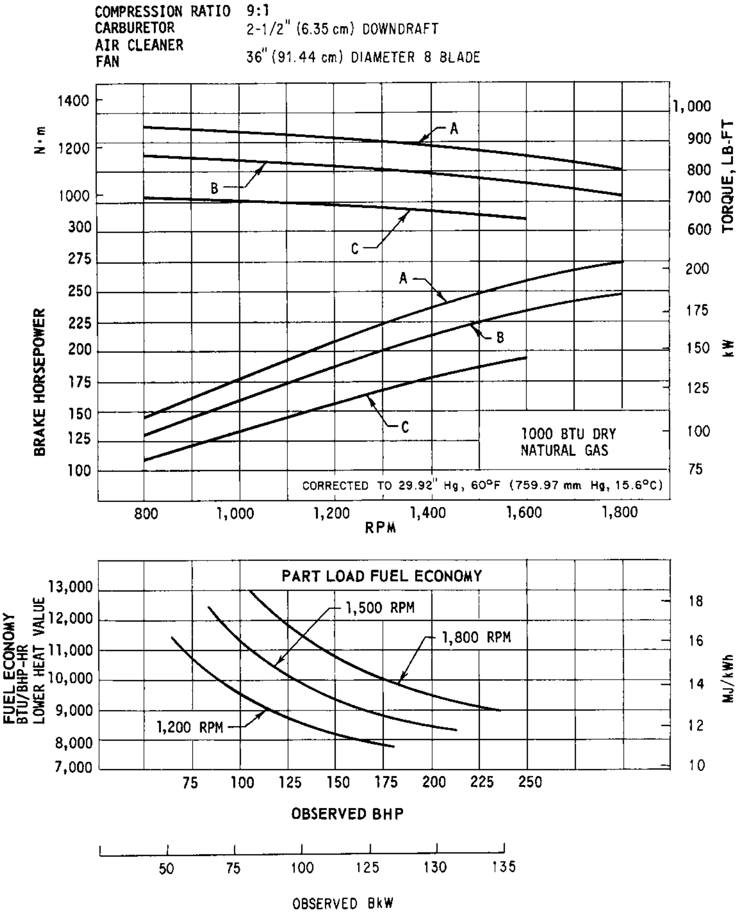

FIGURE 5B Gas engine performance curves: (A) maximum, (B) intermittent, (C) continuous ratings of engines with accessories (Waukesha Motor)

- Variation in the heat-exchanger coolant temperature
- Entrapment of substantial quantities of air in the coolant water
- Inability to maintain a clean cooling system

With any cooling system, one of the most important factors of design is the temperature drop across the engine. Most engine manufacturers desire a temperature differential of no more than 10 to 12°F (5.6 to 6.7°C), and closer values are desirable. A jacket-water temperature across the engine of 170°F (77°C) is preferred, and in high-temperature or waste-heat-recovery systems, temperatures of 200°F (93°C) or more are common and not harmful.

Radiator The radiator cooling system is perhaps the most common and best understood method of cooling. It is based on a closed system of tubes through which the jacket water passes. The heat is dissipated by a fan, creating a stream of moving air passing through

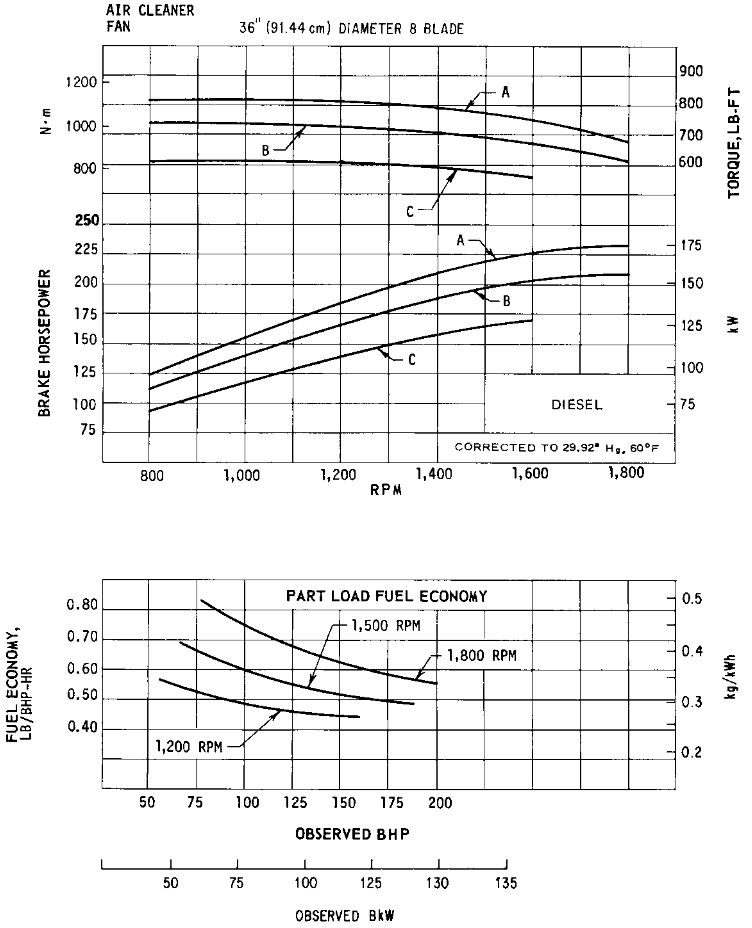

FIGURE 5C Diesel engine performance curves: (A) maximum, (B) intermittent, (C) continuous ratings of engines with accessories (Waukesha Motor)

the tubes. The fan is driven either by the engine or by an auxiliary source of power (Figure 7).

An engine in a fixed outside installation can be cooled without much difficulty. Certain factors must be considered, such as ambient temperature, direction of the prevailing wind, and presence of foreign airborne materials. In high temperatures (usually above 110°F [48°C]), a larger radiator is required. If the prevailing winds are extremely high, the unit can be located to offset normal fan flow. Screening can be used to prevent the clogging of the air passes in the radiator where the atmosphere tends to contain foreign airborne material, such as dust.

Radiator cooling may be used in an inside installation, but there are certain problems which, unless properly anticipated, limit this system. The recirculation of cooling air and the radiation of exhaust heat from the engine create a problem. As was previously pointed out, every 10°F (5.6°C) rise above 60°F (15.6°C) results in a 1% loss in power. When 5 to 10% of the total heat put into an engine is radiated, some means of power ventilation must

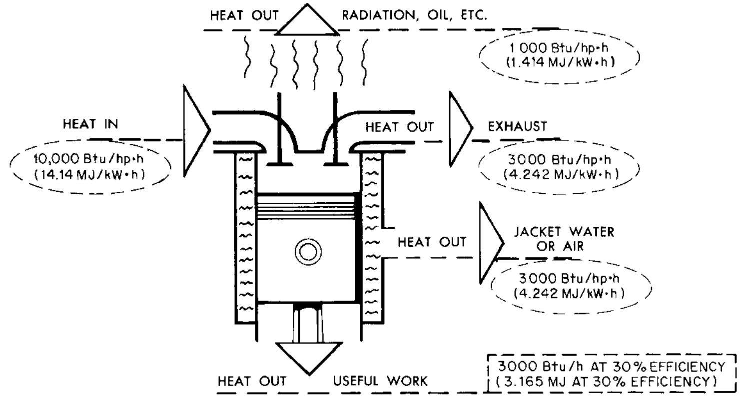

FIGURE 6 Hypothetical heat balance (Waukesha Motor)

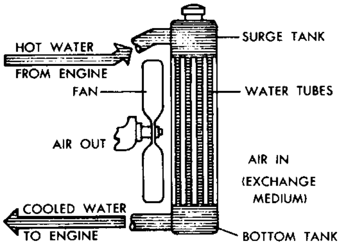

FIGURE 7 Radiator cooling system (Waukesha Motor)

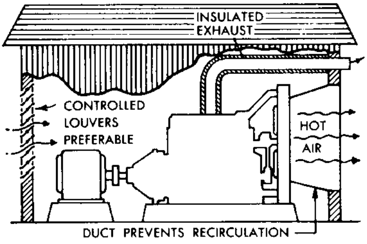

FIGURE 8 Radiator cooling system for an inside installation (Waukesha Motor)

be provided to remove this heat through ducts, louvers, or forced ventilation with a separate fan. An installation of this type is illustrated in Figure 8.

Heat Exchanger The heat exchanger cooling system (Figure 9) is the best system for a stationary engine installation. Using a tube bundle in a closed shell, the cooling exchange medium is water (often called raw water). This water may be plant or process water; it may be recirculated or, in standby installations, allowed to pass to waste. The system has the advantage of the radiator cooling system in that it is self-contained: the quantity and quality of the water in the engine can be controlled. It has the further advantage of not being affected by the flow of heat to air movement if the heat of radiation is taken into account in the design of the system. On the other hand, the cooling medium, unless used in a plant system, is a disadvantage because it is costly. A separate pump is required to provide the necessary water for cooling unless city water or process water is under sufficient pressure.

City Water and Standpipe City water cooling is designed to take water directly from the city main or from the pump the engine is driving. It is used on some emergency or standby installation. It is simple and inexpensive, gives unlimited cooling for moderate-size engines, is easily understood, and will operate instantly in an emergency. On the negative side, the cooling water is wasted, corrosive elements may be introduced into the engine jacket water system, and it may create excessive temperature changes across the engine jacket.

Standpipe cooling (Figure 10) is basically the same as city water cooling except that a thermostatic valve is employed to admit makeup water as required. The vertical pipe is a

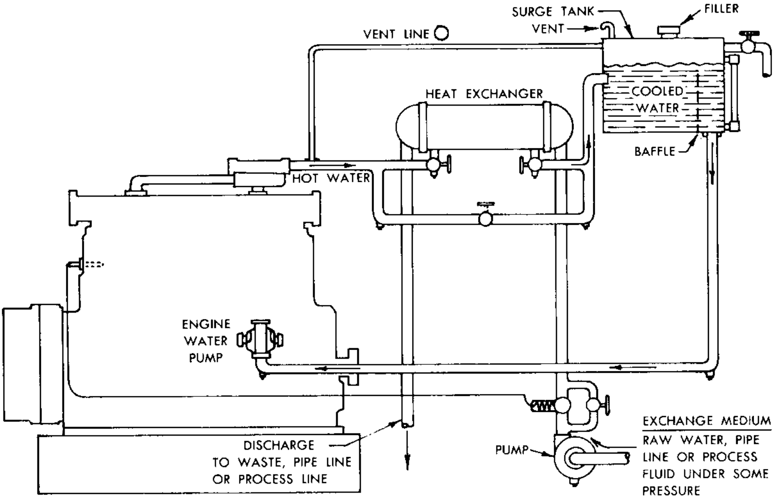

FIGURE 9 Heat exchanger cooling system (Waukesha Motor)

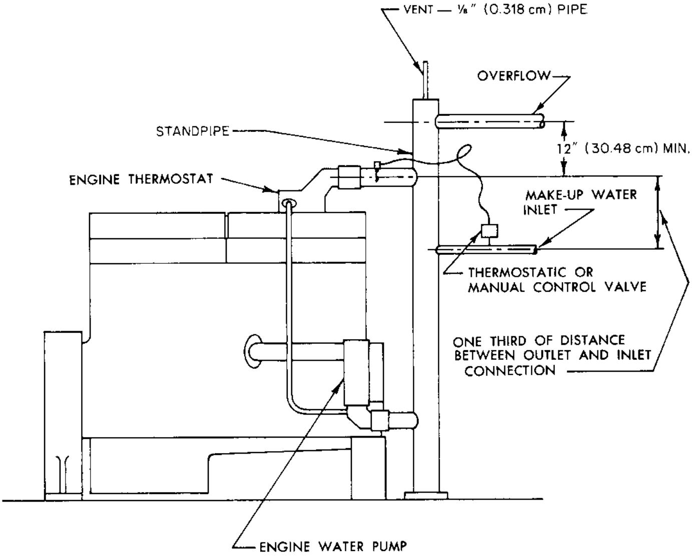

FIGURE 10 Standpipe cooling system (Waukesha Motor)

blending tank into which city water is introduced only in the amount necessary for makeup. The standpipe system is inexpensive and simple to operate.

Ebullition In installations where heat is required for process equipment, a method of high-temperature, or ebullition, cooling is being used as a very economical method, particularly with larger installations. This system has been termed *steam cooling, high-temperature,* or *Vapor-phase* (a registered trademark). In this system, the coolant leaves

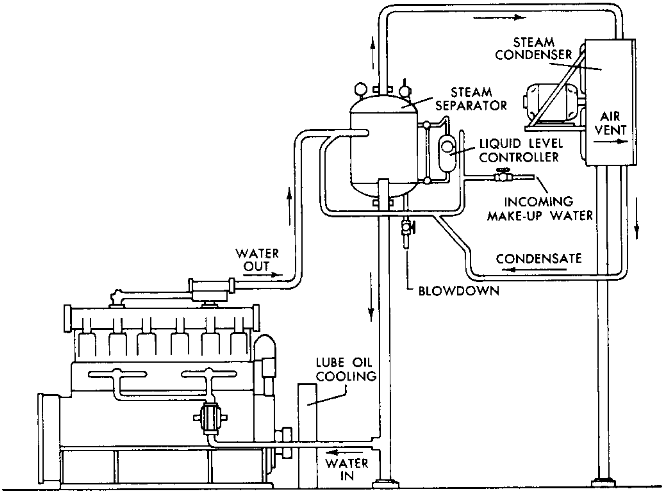

FIGURE 11 High-temperature cooling system (Waukesha Motor)

the engine at a temperature equal to or above its atmospheric boiling point and under sufficient pressure to remain liquid until discharged from the engine into a flash chamber, where a drop in pressure causes the formation of steam, which is condensed and returned to the engine at very near the discharge temperature. A schematic of this system is shown in Figure 11. This system has the advantages of a very small temperature differential across the engine, which minimizes distortion of all working parts, and a constant working temperature regardless of load. Because of the higher working temperatures, the combustion area and crankcase of the engine have fewer liquid by-products of combustion and corrosive materials. Of prime importance is the waste heat that can be recovered for plant process with a very small amount of makeup water for cooling.

Cooling Tower Cooling towers are used in some large or multiple-engine installations. Through the use of a current of air, produced either by a natural draft or by mechanical means, a tower causes a sensible heat flow from the cooling water to the air. Atmospheric, or natural, draft towers depend upon natural wind velocities and thus can vary widely. Mechanical draft towers, where the air supply can be controlled, can be put in any area, but the limit to their cooling capacity is the power required to operate them. As the water volume increases, the volume of air required and the pressure the fan has to operate against increase. A point is reached where the cost of installation and operation becomes prohibitive. A diagram of a system that combines components of the cooling systems mentioned plus the waste-heat recovery system silencer, to be mentioned later, is shown in Figure 12.

AIR-INTAKE SYSTEMS

A most important consideration in the application of an engine to any pump drive is the engine's ability to "breathe." As air is required for combustion, the design engineers of any project must take into account the necessary provisions for this air. The environment, the service, the speed range of the engine, the duty cycle, and the location from which the combustion air is to be taken are of vital importance.

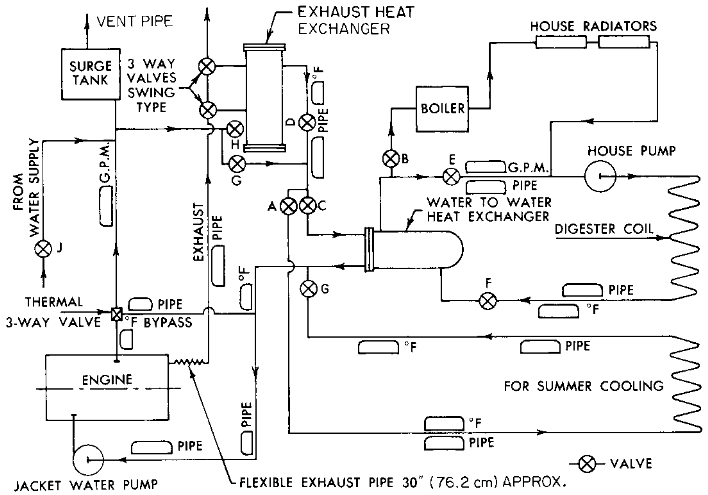

FIGURE 12 Complete cooling system, including waste-heat recovery (Waukesha Motor)

The first step in the selection of any intake system is to determine the volume of air, in cubic feet per minute (cubic meters per second) required for combustion, which may be calculated by the formula:

$$V_{\text{ideal}} = \frac{B^2 \times S \times \text{rpm} \times N}{C \times K}$$

where B = cylinder bore, in (cm)
S = piston stroke, in (cm)
rpm = engine speed, revs/minute
N = number of cylinders
C = 2,200 for V_{ideal} in CFM or 76.39×10^6 for V_{ideal} in m^3/s
K = 1 for two-stroke cycle and 2 for four-stroke cycle

Volumetric efficiency, defined as the ratio of actual air flow to ideal air flow, will vary with engine design, but an average of 80% may be used to determine the air cleaner size. Two-stroke cycle engines will require approximately 140% air flow calculated by the above equation. For supercharged and turbocharged engines, the air flow requirements should be obtained from the manufacturer.

The two basic cleaners available are wet and dry. The wet, or oil-bath, cleaner consists of either an oil wire mesh or an oil bath through which the air must pass. A dry cleaner uses a paper or cloth filter that traps dust, lint, and so on but allows the air to pass through.

The installation of a suitable air cleaner is important. In cases where adequate air can be supplied through proper ventilation of the area surrounding the engine, it is best to mount the cleaner on the engine. If it is necessary to bring air to the engine from outside the area of the building, certain design factors must be considered. The pipe connections from an outside cleaner should be tight and mechanically strong, and fabric hose should not be used unless the length is relatively short. The air to the engine should not be heated by close proximity to the engine or any other heating device because, as previously mentioned, power loss occurs with air temperatures above 60°F (15.6°C). To avoid restrictions in the system, there should be no sharp bends in the piping. Finally, any outside air cleaner must be designed so moisture such as rain or snow cannot enter the system.

The air cleaner system on a turbocharged engine must be able to remove any impurities in the air that would be detrimental to the efficiency of the turbocharger. Because of the increased air requirements, a larger air-cleaner system must be used on such units.

EXHAUST SYSTEMS

An engine consumes a large volume of air for combustion, and that volume must be removed after combustion. It is necessary that the exhaust back pressure be kept at a minimum while this volume is being removed. The exhaust piping should be properly sized, and long sweep elbows should be employed if necessary. Unless the back pressure is kept low, the following conditions can result:

- Loss of power
- Poor fuel economy
- High combustion temperatures with increased maintenance
- High jacket water temperatures
- Crankcase sludging with resulting corrosion and bearing wear

All internal combustion engines create noise. Depending upon the location of the engine, this noise can be a problem. Normally, when measured from a distance of about 10 ft (3 m), an unmuffled engine creates a decibel noise level ranging from 100 for the small- and medium-size engine to 125 for the larger engine. Thus most engine installations incorporate some form of exhaust silencer, or muffler. Depending upon the degree of silencing, a muffler will reduce the unmuffled decibel reading by 30 to 35 dB. Various types are manufactured to meet the required conditions and are classified as follows:

- Standard or industrial
- Semiresidential (high-degree)
- Residential or hospital (supercritical)

The basic exhaust silencer is designed as either a dry type or wet type. The latter is used in installations such as sewage or water treatment plants, where the recovery of heat for plant processes is important. Basically this type may be classified as a low-pressure boiler. Water is admitted to the silencer through tubes or coils to pick up the heat from the exhaust. As shown in Figure 6, approximately 30% of the total heat input into the engine is exhausted. The wet-type silencer is designed to regain about 60 to 70% of this beat. This silencer has an advantage in its ability to operate either wet or dry. Thus when heat is not required, it may be operated dry and vice versa.

STARTING SYSTEMS

Starting methods for engines fall into two broad categories: direct and auxiliary.

Direct The direct system, used primarily with large engines, employs some means of exerting a rotating force on the crankshaft, such as the introduction of high-pressure air directly into the cylinders of the engine. A direct system on small air- or water-cooled engines using either a rope or a hand crank has to a large extent been discarded in favor of an auxiliary method.

Auxiliary The auxiliary system employs a small gear that meshes with a larger gear (ring gear) on the engine flywheel. The ratio of the number of gear teeth on the large gear to those on the small gear is called the *cranking ratio.* Generally, the larger the ratio, the better the cranking performance. The auxiliary system uses several means to drive the small gear:

- Electric motor
- Air motor
- Hydraulic motor
- Auxiliary engine

ELECTRIC MOTOR The electric motor may be either dc or ac. The dc motor most commonly used is available in 6, 12, 24, or 32 V. The voltage size will depend upon the size of the engine, the ambient temperature, and the desired cranking speed of the engine. The dc system requires a source of outside power, usually in the form of a storage battery. To assure prompt starting, a charging system for the battery is required in the form of either a charging generator driven by the engine or an ac-powered battery trickle charger. The latter is recommended for standby installations where an engine-driven charging generator functions only when the engine is operating. During idle periods, the battery will lose its charge unless maintained by a trickle charger. In recent years, there has been a trend toward the use of an ac generator, or alternator, which has the advantages of small size, higher voltage and amperage, competitive price, and good charging ability under idle speed conditions.

Another type of electric motor is a line voltage starter available in 110, 220, or 440V ac. It has the advantages of faster and more powerful cranking, the elimination of the battery and charging system, less maintenance, and sustained cranking through unlimited available electric power. Its disadvantages are a higher initial cost, the requirement of high line voltage at the site, the danger to personnel due to the high voltage, and the requirement to conform to existing wiring and installation codes.

AIR MOTOR The air motor, which is usually of the rotary-vane type, uses high-pressure air in the range of 50 to 150 lb/in^2 (340 to 1030 kPa) to turn it in starting the engine. It is mounted on the engine flywheel housing to mesh with the gear on the flywheel in the same manner as the electric motor. An outside source of air from an air compressor, usually with a 250-lb/in^2 (1720-kPa) capacity, is required. A pressure-reducing valve is installed in the line to the engine. The high-pressure air stored in an adequate receiver is sufficient for several starting cycles. This starting system has the advantages of faster cranking, sustained cranking as long as the air supply lasts, suitability in hazardous locations where an electric system might be dangerous, and ability to operate on either compressed air or high-pressure natural gas. Its disadvantages include a higher initial cost, the requirement of an air-compressor system, and, finally, a shutdown condition if the air supply is depleted before the engine starts.

HYDRAULIC MOTOR The hydraulic motor system consists of the motor, an oil reservoir, an accumulator, and some means of charging the accumulator. The accumulator, which is a simple cylinder with a piston, is charged on one side with nitrogen gas. As the hydraulic fluid, usually oil, is pumped into the other side, the gas is compressed to a very high pressure. When released, the fluid turns the motor, which in turn rotates the engine. The system can be charged by hand, with an engine-driven pump, or with an electric motor-driven pump. Generally, an engine-driven or electric-motor-driven pump is used in conjunction with the hand pump in case of an engine or electrical failure. This system has the same basic advantages of the air motor except that there is no prolonged starting. If the engine is in good operating condition, the cranking is fast and a start is instantaneous, but, if not, it is necessary to recharge the system before another start can be made.

AUXILIARY ENGINE A small auxiliary air-cooled or water-cooled engine is sometimes employed for starting. It may be mounted on the engine in the same manner as the other systems, or a belt drive may be employed. Some form of speed reduction is required to reduce the higher speed of the auxiliary engine to that required for proper cranking. The principal advantage of such a system is a complete independence from outside sources of power, such as batteries, air, or pumps, but this is offset by a higher initial cost and the required regular maintenance of the engine.

IGNITION SYSTEMS

The internal combustion engine requires some means of igniting the combustible charge in the cylinder at the proper time. Today's high-compression gasoline and gas engines demand a system that will produce a high-tension spark across a short gap in the combustion chamber for the ignition of the charge. It is obvious that the design of the combustion chamber must be such that this combustible mixture of fuel and air is present between the discharge gap when the spark occurs; otherwise, ignition will not take place.

Ignition systems for gasoline or gas engines are considered high or low tension. The energy system for the high-tension system is either an electric generator and battery or a magneto. The generator and battery produce a direct current at 6 to 12 V potential, and the magneto produces an alternating current with higher peak voltages. With either energy source, this system has a primary circuit for the low-voltage current and a secondary circuit for the high-voltage current.

The primary circuit consists of the battery, an ammeter, an ignition switch, a primary coil, and breaker points and a condenser in the distributor. When the ignition switch and the breaker points close, a current flows through the circuit and builds up a magnetic field in the primary coil. Opening the breaker points breaks this circuit, causing the magnetic field to start collapsing. As the field collapses, it produces a current that flows in the same direction in the primary circuit and charges the condenser plates. The condenser builds up a potential opposing flow, which discharges back through the current. This results in a sudden collapse of the remaining magnetic field and the induction of a high voltage into the secondary winding of the coil. The breaker points are opened and closed by a cam which is engine-driven, usually at half engine speed.

The secondary circuit consists of the secondary coil winding, the lead to the distributor rotor, the distributor, the spark plug leads or wires, and the spark plug. A magneto eliminates the battery, but includes in its construction the balance of both primary and secondary circuits. It may have either a rotating coil and stationary permanent magnets or a stationary coil and rotating magnets. The relative movement of the primary coil winding and the magnets induces an alternating current in the primary circuit, the breaking of which induces a high-voltage current in the secondary circuit.

The development of the modern engine has required many refinements in spark plug design, but basically a spark plug consists of two electrodes, one grounded through the shell of the plug and the other insulated with porcelain or mica. The insulated electrode is exposed to the combustion. The heat flow occurs from this electrode to the spark plug shell through the grounded electrode.

Recent developments in ignition systems have produced the low-tension and breakerless systems. The breakerless system has eliminated most of the moving parts in the distributor system. The breaker points in the distributor system are actually a switch that opens and closes the primary circuit of an ignition coil. In the breakerless system, the use of solid-state devices provides a switch with no moving parts to wear or require adjustment.

The low-tension magneto system has been developed to reduce electrical stresses in the ignition circuit. The secondary coil has been removed from the magneto proper and relocated near each spark plug. The low voltage generated by the magneto is transmitted through the wiring harness to secondary coils, which then step up to the voltage to be transmitted through short leads to the spark plug. These leads may be insulated to withstand the stresses imposed upon them. This results in a minimum of electrical stresses with a resulting longer life of all components of the system.

As was mentioned previously under fuel systems, the diesel engine used the heat of compression for ignition; thus no auxiliary systems, such as the systems mentioned above, are required. The fuel is injected into the combustion chamber under relatively high pressure through the use of a fuel pump and injection nozzle. This system may be either an individual pump and nozzle for each cylinder, commonly called a *unit injection,* or a multicylinder pump that maintains a high pressure in a common fuel line connected to each injection nozzle. The latter is normally called the *common rail system.*

ENGINE INSTALLATIONS

Foundation The correct foundation, mounting, vibration isolation, and alignment are most important to the success of any engine installation. All stationary engines require a foundation or mounting base. There are many variations, but all basically serve to isolate the engine from the surrounding structures and absorb or inhibit vibrations. Such a base also provides a permanent and accurate surface upon which the engine and usually the pump may be mounted.

To meet these requirements, the foundation must be suitable in size and mass, rest on an adequate bearing surface, provide an accurately finished mounting surface, and be equipped with the necessary anchor bolts.

The size and mass of the foundation will depend upon the dimensions and weight of the engine and the pump (if a common base is considered). The following minimum standards should be followed:

1. Width should exceed the equipment width and length by a minimum of 1 ft (0.3 m).
2. The depth should be sufficient to provide a weight equal to 1.3 to 1.5 times the weight of the equipment. This depth may be determined by the following formula:

In USCS units
$$H = \frac{(1.3 - 1.5)W}{L \times B \times 135}$$

In SI units
$$H = \frac{(1.3 - 1.5)W}{L \times B \times 2162}$$

where H = depth of foundation, ft (m)
W = weight (mass) of equipment, lb (kg)
L = length of foundation, ft (m)
B = width of foundation, ft (m)
135 = density of concrete, lb/ft^3 (2162 kg/m^3)

The soil-bearing load in pounds per square foot (kilograms per square meter) should not exceed the building standard codes. It may be calculated by the formula

$$\text{Bearing load} = \frac{(2.3 - 2.5)W}{B \times L}$$

Foundation or anchor bolts used to hold the equipment in place should be of SAE grade No. 5 bolt material or equivalent. The diameter, of course, is determined by the mounting holes of the equipment. The length should be equivalent to a minimum embedded length of 30 times the diameter plus the necessary length for either a J or an L hook. An additional 5 to 6 in (13 to 15 cm) should be provided above the top surface of the foundation for grout, sole plate, chocks, shims, equipment base washers, and nuts, plus small variations in the surface level. Around the bolts, it is a good practice to place a sleeve of iron pipe or plastic tubing to allow some bending of the bolts to conform with the mounting hole locations. This sleeve should be about two-thirds the length of the bolt, with its top slightly above the top surface of the foundation to prevent concrete from spilling into the sleeve.

Sole plates running the length of the equipment are recommended for mounting directly to the foundation. Made of at least $\frac{3}{4}$-in (19-mm) hot- or cold-rolled steel and a width equivalent to the base-foot mounting of the equipment, they will provide a level means of mounting and will avoid variations in the level of the concrete. These plates should be drilled for the mounting holes and drilled and tapped for leveling screws, which will permit the plates to be leveled and held during the pouring of grout.

Alignment Although the alignment will vary with the type of engine and the pumping equipment, the basic objective remains the same. The driven shaft should be concentric with the driver shaft, and the centerlines of the two shafts should be parallel to each other. Rough alignment should be made through the use of chocks and shims. A dial indicator should be used to check deflection by loosening or tightening the anchor bolt nuts until there is less than a 0.005-in (0.13 mm) reading at each bolt. Shims should be added or removed to arrive at this point. A final check should be made with all the conditions “hot,” as the engine and its driven equipment expand at the rate of 0.000006 in/°F (0.27 μm/°C) above ambient hot to cold. Although the coupling, or driving member between the engine and the pump is not discussed in this section, it must be considered in the final alignment.

Vibration Isolation It is desirable to isolate the engine, and at times the pumping equipment, from the building structure because of vibrations. Cork (Figure 13) is used in the larger and heavier installations. A combination of cork and rubber pads may be used at each mounting hole on small- or medium-size installations, and spring isolators may be used on a complete installation if flexible hoses are used for fuel, water, and air connections where required. The manufacturer of the engine and the pumping equipment should be consulted in the use of any isolating material or device.

Vibrations are closely associated with the driving and driven equipment, couplings, and other connections. These linear vibrations may be caused by improper supports of the unbalanced parts, which produce a *torsional* vibration. An understanding of this vibration is important because its elimination is the responsibility of the engine and the driven-equipment manufacturer. It is complex and cannot be detected without the use of calculations and special instruments.

The basic concept involves an elastic element, such as an engine crankshaft, which tends to twist when any firing impulses are applied. When these forces are removed, the elastic body will try to return to its original position. The driven mass and the connecting elements tend to resist these external impulses. The natural elasticity of the crankshaft and its connecting system allows a small amount of torsional deflection and tends to

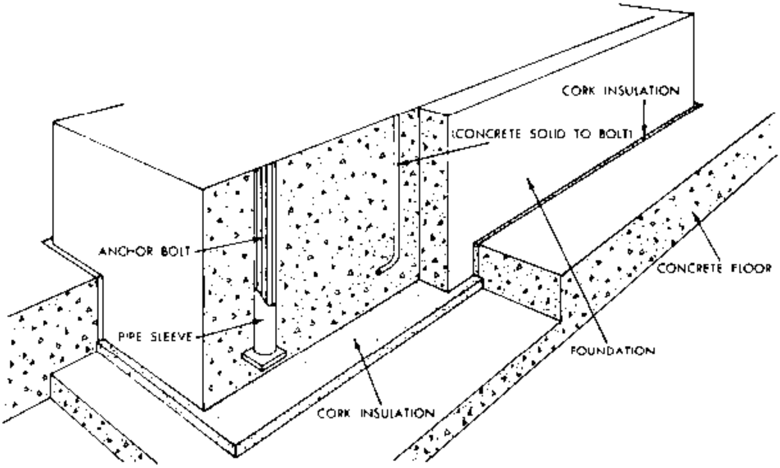

FIGURE 13 Engine foundation installation (Waukesha Motor)

reduce the deflection as the external impulses reduce in force. Other reciprocating forces in the engine and external forces in the driven equipment may excite vibrations in the entire system. When all these forces come into resonance with the natural frequency of the entire system, torsional vibration will occur. This vibration may or may not be serious but, being complex, cannot be solved hastily.

The engine and pump manufacturer designs and constructs the product so critical harmonic vibrations will not be present under normal speeds and loads. However, there is no way to control the combination. An analysis of the complete system should be made. This requires a study of the mass elastic system of the combination, involving the mass weight and radius of gyration of all rotating parts. This study should be made either by the engine or pump manufacturer or by a torsional-analysis specialist.

FURTHER READING

Gunther, F. J. "Gas Engine Power for Water and Wastewater Facilities." *Water & Sewerage Works,* **112** and **113** (November 1965 to July 1966).