●●● POWER
ENGINEERING

Fourth Class

Edition 3.5

Types of Prime Movers and Heat Engines

Part B

Unit B-7

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PanGlobal
Partner in Education

1–1339 40 Ave NE
Calgary, Alberta
T2E 8N6

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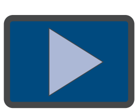
MEDIA 	Media icons show that some form of supporting medium is available. These media may include videos, animations, 2D and 3D models, multi-views of cutaways, simulations, and more. Media elements are available to registered textbook purchasers online via MyPower Study.
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UNIT B-7

TYPES OF PRIME MOVERS AND HEAT ENGINES

Unit Introduction

The systems discussed in this unit explore industrial applications of thermodynamic theory. Power Engineers must understand the technology, systems, and equipment used to generate power in thermal plants. The Power Engineer must also comprehend how thermal energy is converted into other forms of energy. Thermodynamic principles indicate that heat and work are mutually convertible. So, as heat is converted into mechanical energy, it produces work. A basic understanding of how prime movers convert heat to work is central to this knowledge.

This unit introduces the principles behind the operation of prime movers, including many familiar types of heat engines. Components of these prime movers, and how they act together to produce power, will be discussed. As usual, operation and maintenance will be stressed, to ensure equipment longevity and efficiency in operation.

This content will help to:

- Differentiate between heat engines and prime movers.
- Understand principles to safely operate prime movers.
- Explain the different sources of energy that can be used effectively in a power plant.

Unit Rationale

Heat engines and prime movers have ancillary systems, such as cooling towers, lubricating systems, and speed governing systems. These are integral to the operation of steam turbines, gas turbines, and internal combustion engines to maintain proper temperature, pressure, and to avoid unsafe operating conditions.

It is essential for a Power Engineer to study the principles of operation and construction, and to understand how those components play an important role to their respective equipment.

CHAPTER 1

Heat Engines and Prime Movers

Learning Outcome

When you complete this chapter you should be able to:

Discuss the historical conversion of heat energy into mechanical energy.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Differentiate between the terms "heat engine" and "prime mover."*
2. *Discuss the history of the steam engine and the expansive power of steam.*

Chapter Introduction

This chapter examines the devices that convert energy into mechanical work, which are categorized as prime movers and heat engines. The steam engine – a prime mover – is primarily of historical interest. However, it is used here to explain the conversion of heat into mechanical work. As well, the steam engine demonstrates how steam's expansive properties can be used to produce work.

Steam engines have components that are similar to those of some other prime movers, as well as parts similar to those found in air compressors and refrigeration compressors. In this regard, studying steam engine construction can help understand the construction and operation of other pieces of equipment Power Engineers routinely operate.

This chapter also covers startup and routine operation of steam engines. Some of this information can be directly transferred to the startup and operation of other similarly constructed machines.

Objective 1

Differentiate between the terms "heat engine" and "prime mover."

Prime Movers

A **prime mover** is a machine that converts a naturally occurring source of energy into mechanical energy. Below are some naturally occurring energy sources.

Potential energy: Potential energy, when in the form of water stored behind a hydro-electric dam, can be converted by a water turbine to mechanical energy. The turbine then drives an alternator.

Kinetic energy: The kinetic energy of wind can be converted to mechanical energy using a wind turbine.

Chemical energy: Through a combustion process, the chemical energy of fuel can be converted to heat energy. It can then be converted to mechanical energy using internal and external combustion engines.

Nuclear energy: Through atomic fission, nuclear energy can be converted to heat energy. It is then converted to potential energy in the form of high pressure steam. Finally, it is converted to mechanical energy using steam turbines.

Solar energy: Using mirrors, lenses and boilers, solar energy can be converted to heat energy. It is then converted to potential energy in the form of high pressure steam. Finally, it is converted to mechanical energy by steam turbines.

In the examples above, the water turbines, wind turbines, **internal combustion engines**, **external combustion engines**, and **steam turbines** are all prime movers, because they convert naturally occurring energy into mechanical energy.

Another way to think of a prime mover is as a machine that directly causes motion in another machine. For example, a machine that drives an electric generator (such as a steam turbine, **gas turbine**, or wind turbine) is called the prime mover of the generator. The prime mover is often called a "driver."

Note that electric motors are not considered prime movers, because they do not convert a naturally occurring energy source to mechanical energy. Rather, electric motors are considered to be secondary movers.

As a group, prime movers include:

a) Internal combustion engines
   - Gasoline engines
   - Diesel engines
   - Gas Turbines

b) External combustion engines
   - Steam engines
   - Steam turbines

c) Wind turbines

d) Water turbines

Heat Engines

Some prime movers are also **heat engines**. A heat engine is one that converts heat energy to mechanical energy through a series of repetitive thermodynamic operations. These operations include processes such as combustion, compression, expansion, boiling, condensation, and cooling. Though heat energy occurs naturally, the heat converted by a heat engine is usually produced from other naturally occurring energy sources such as solar, nuclear, and chemical.

A heat engine may be a single self-contained machine, capable of carrying out all of the thermodynamic process without any additional equipment. For example, a diesel engine has all the parts necessary to burn fuel with air and harness the expansive energy of heated gas.

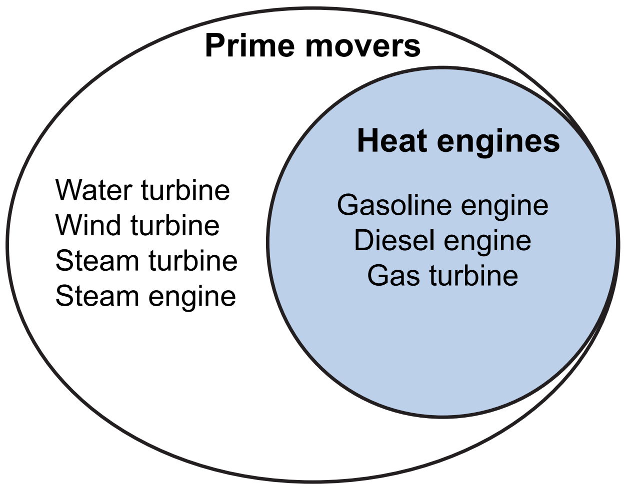
However, a heat engine may also be a complex system of various machines that, when working together, completes the necessary thermodynamic processes. For example, a steam turbine is merely one component (the "prime mover") of a larger system used to convert nuclear, solar, or chemical energy to mechanical energy. This complex system comprised of a boiler, a water pump, a condenser, a prime mover, and a heat source is called a **Rankine Cycle** heat engine. The steam turbine is only one component in the system.

In a Rankine Cycle engine, a boiler exposes water to heat, producing high pressure steam. The steam passes through a steam turbine that produces mechanical work. Neither the boiler nor the steam turbine is a heat engine. However, together they act as a heat engine "system," and convert heat into mechanical work. Thus, a steam turbine, though a prime mover, is not a heat engine.

The most familiar heat engines are single self-contained machines, such as **diesel engines**, **gas engines**, and gas turbines. In each case, fuel is burned to produce heat in a working fluid (combustion gases and air). This heat, combined with the internal design of the engine, initiates a thermodynamic process in the working fluid. This produces mechanical work at the engine shaft.

Figure 1 shows how prime movers and heat engines are related. Note that all heat engines are prime movers, but not all prime movers are heat engines.

Figure 1 – Prime Movers and Heat Engines



Energy Sources

Although there are many naturally occurring energy sources, only a few are currently used for large-scale power production. These include the potential, kinetic, chemical, nuclear, and solar energy sources already mentioned. These energy sources suit different types of heat engines and prime movers.

Chemical energy sources continue to be extremely important. These include gaseous, liquid, and solid hydrocarbon-based fuels, such as natural gas, fuel oil, coal, and biomass.

Steam plants that operate on the Rankine Cycle are very common because they can use a wide variety of heat sources, including hydrocarbon fuels, waste process heat, solar energy and nuclear energy. In addition, their cycle of operations has the highest overall efficiency. Internal combustion engines, on the other hand, are restricted to using liquid or gaseous hydrocarbon energy sources.

Objective 2

Discuss the history of the steam engine and the expansive power of steam.

Steam Engine

Historically, steam engines were the most important and widely used prime mover. However, steam turbines, combustion engines, and electric motors have made them nearly obsolete. Part of the reason for this is the steam engine's greater complexity and lower efficiency than the steam turbine. As well, the steam engine discharges lubricating oil with its exhaust steam. This makes it difficult to recover the condensate and re-use it for boiler feedwater.

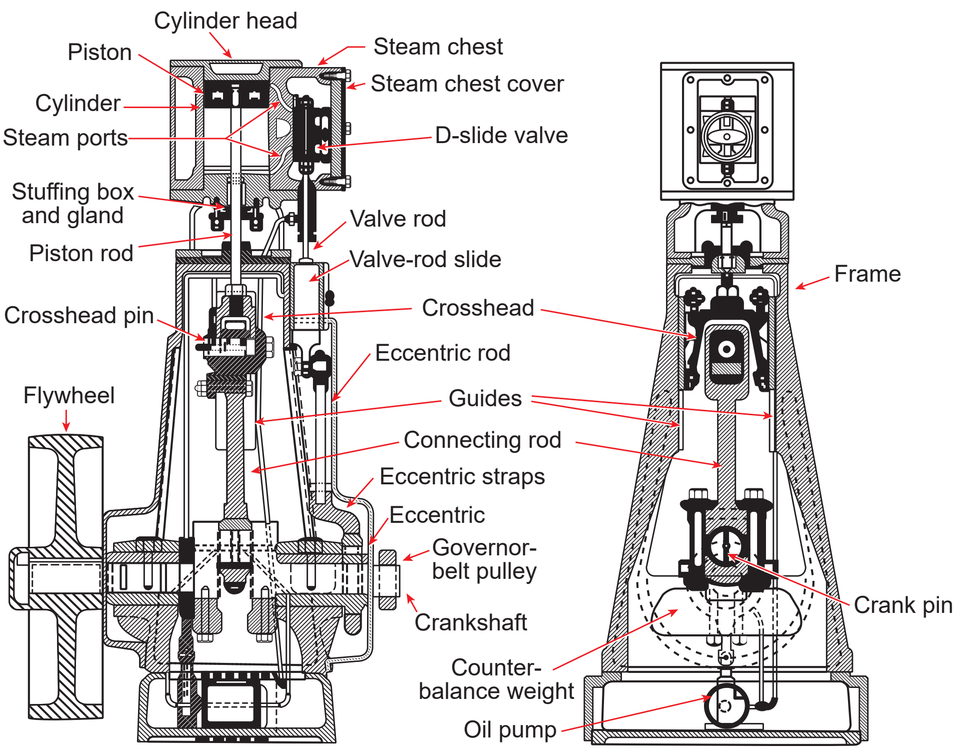
Today steam engines are rarely seen in service. However, they are still used in a few specialized applications.

a) To drive slowly rotating equipment, when reduction gearing is not used.
b) To drive equipment that must occasionally be driven in the reverse direction without the use of gearing.
c) To power reciprocating pumps.
d) To power restored vintage locomotives, sawmills, steamships, and agricultural traction engines.

Steam Engine Construction

Figure 2 shows two sectional elevations of a simple steam engine. This engine is described as a single cylinder, **double-acting**, vertical engine with a **D-slide valve**.

Figure 2 – Sectional Elevation of a Vertical Engine



Refer to Figures 2 and 3(a). Steam, from the main steam pipe, enters the **steam chest** via the **throttle valve** (not shown). The **slide valve** controls the steam admission to, and the exhaust from, the engine cylinder.

The slide valve is driven by the **eccentric**, the **eccentric rod**, and the **valve rod** (Figures 2 and 3(b)). The eccentric rotates with the crankshaft, and converts rotary motion to the reciprocating motion required by the slide valve. The slide valve is continually repositioned with respect to the position of the crankshaft (and therefore the position of the piston). In this way, steam admission and exhaust is carefully timed.

The engine shown is called a "double acting" engine because steam pressure is alternately applied to the top or bottom of the piston. The engine thus produces power on both the upward and the downward stroke. Figure 3 shows the position of the slide valve when it is about to admit steam to the top of the piston. Note that steam is permitted to pass from the bottom of the piston through the underside of the slide valve to exhaust.

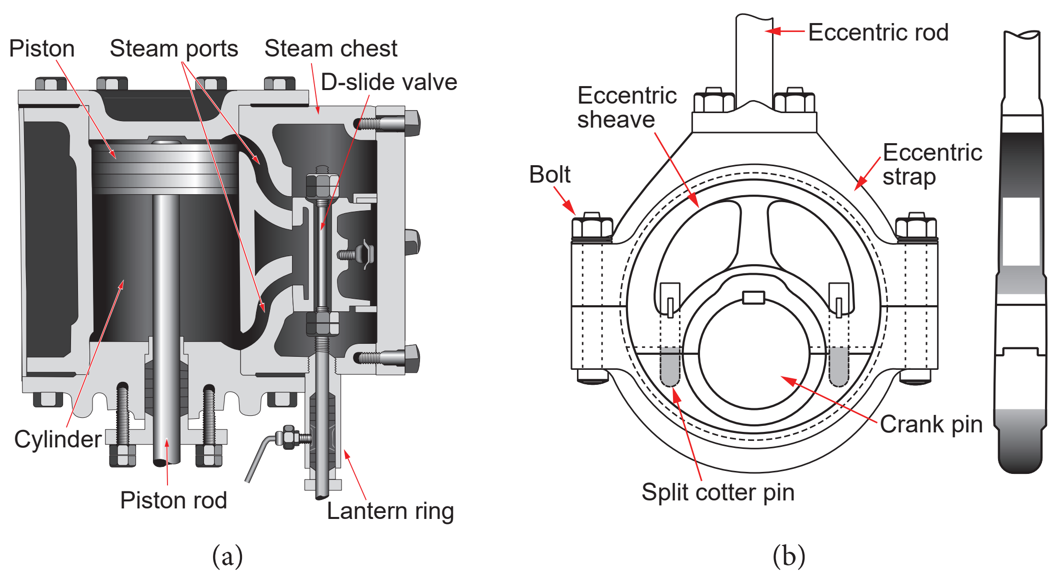
When the piston has completed about 1/4 to 1/3 of its stroke (depending on the engine load), the steam supply is cutoff, with both steam inlet ports covered by the slide valve.

At this point, the steam that remains in the cylinder maintains force on the piston by expanding throughout the remainder of the stroke. Finally, the slide valve opens a passage to the exhaust and allows the steam on this side of the piston to escape, in preparation for the return stroke under the action of live steam on the other side of the piston.

Cutting off the steam supply and allowing the steam in the cylinder to expand is termed "expansive" use of steam. This results in the most economical engine operation. For specific operation requirements, slide valves can be set to admit steam continuously throughout the entire stroke. This is usually only done when maximum power production is more important than the economic usage of steam.

Figure 3(a) shows an engine cylinder in section, with piston and steam valve shown. Figure 3(b) shows an eccentric **sheave**.

Figure 3 – Steam Engine Cylinder and Eccentric



The eccentric, shown in Figure 3(b), is a disk fixed on the crankshaft in such a way that the center of the disc is "eccentric" or "off center" with the center of the shaft. The disk is termed the sheave of the eccentric, and is in built in two halves. The halves are secured by bolts and split by cotter pins.

The band surrounding the sheave is called the strap. The sheave rotates inside the strap in the same way as the crank pin rotates in the connecting rod head. The eccentric rod is attached to the strap, and the slide valve receives a reciprocating motion from it. This motion is similar to that received by the piston from the crank pin, but on a reduced scale.

As the slide valve moves endwise on the valve seat, steam is admitted through the steam ports. The steam admitted to one side of the piston it is at boiler pressure, and the other side of the piston is at lower pressure. The difference between these pressures causes the piston to move along the cylinder. The force exerted on the piston is transmitted through the **piston rod**, the **connecting rod**, and the **crank pin** to the **crankshaft**. The crankshaft converts the reciprocating motion to a rotary motion.

The **crosshead** guides the piston rod directly into the cylinder, without any side-to-side motion. It also transfers the reciprocating motion of the piston rod to the rotational motion of the crankshaft via the connecting rod. The valve rod slide serves a similar purpose between the eccentric rod and the valve rod. It facilitates the transfer of rotary motion of the eccentric via the eccentric rod to the reciprocating motion of the valve rod.

Lubricators are provided at locations that slide or rub. The lubricators feed oil between the sliding surfaces to reduce friction and wear.

Steam should not leak past the piston rod or valve rod. Therefore, packing boxes filled with flexible packing are provided at each of these locations. The packing is squeezed tightly into the box around the rod by a gland that is held in place by a covering nut, or studs and nuts in the cylinder body.

Drain cocks are fitted into the lowest part of the cylinder and valve box for the removal of any water caused by the condensation of steam. See Figure 5(b).

In most steam engines, the admission of steam stops before the end of the stroke, to allow work to be done by steam expansion. This develops a greater force on the piston at the beginning of the stroke instead of at the end of the stroke. Thus, the piston moves faster at the beginning of the stroke rather than at the end, creating uneven speed development.

A **governor** regulates engine speed with the change in load requirements. The **flywheel** is often fitted to dampen or even out the changes of speed caused by varying steam pressure and loads. It also allows the crankshaft to continue to rotate even when no work is done by the piston. The flywheel stores the excess energy during the stroke, when steam is admitted, and releases the energy at the end of the stroke, when steam is exhausted.

The frame of the steam engine holds the parts together in their relative positions. It also provides a means of securing the engine solidly on its foundation.

Figure 4 shows a sectional view of a small vertical single cylinder, double-acting steam engine. It has with a piston type steam slide valve in the steam chest, and an **inertia governor** in the flywheel.

Figure 4 – Automatic Inertia Governor on Flywheel

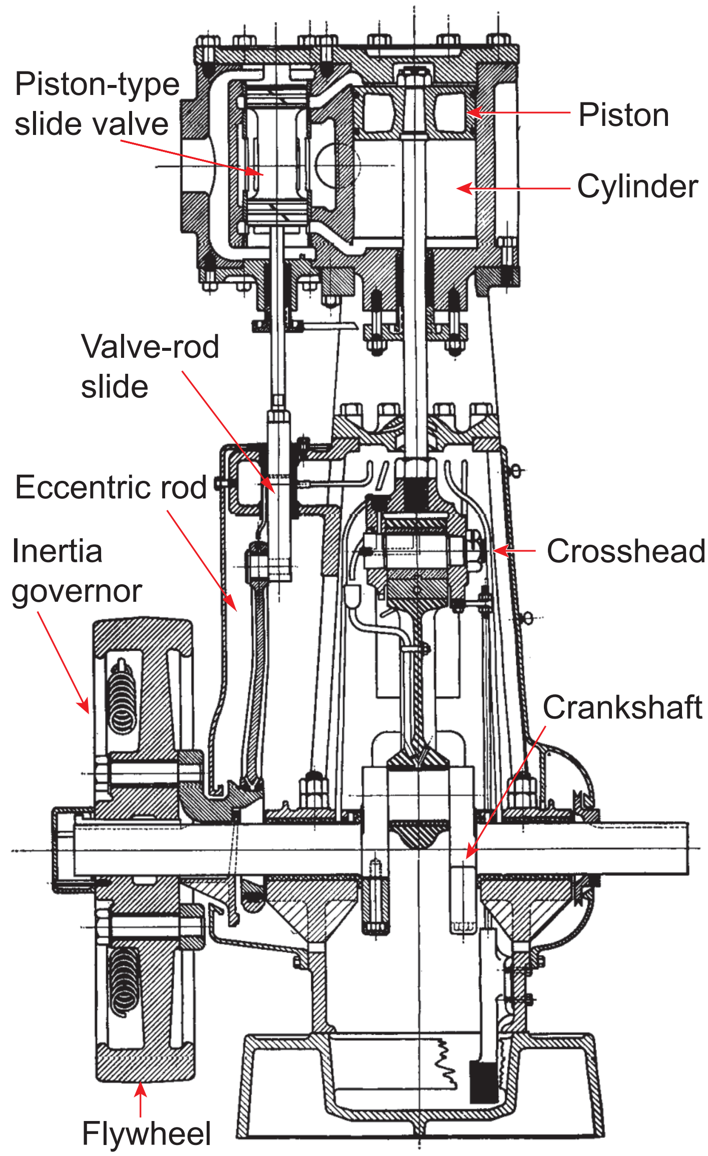
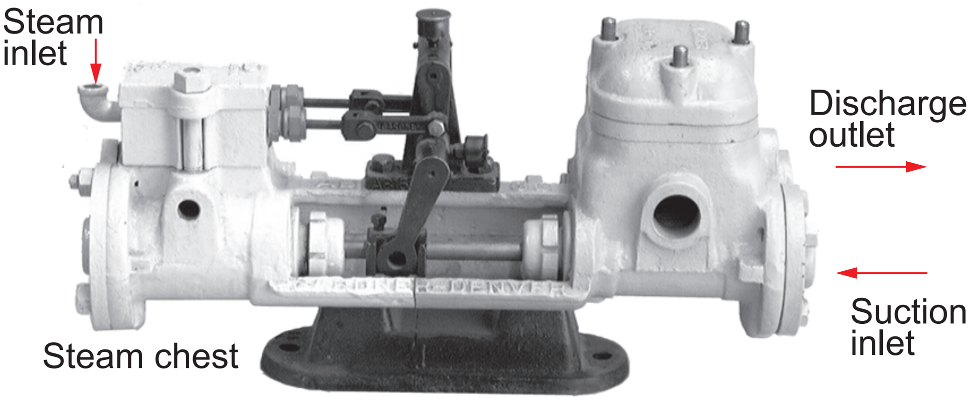
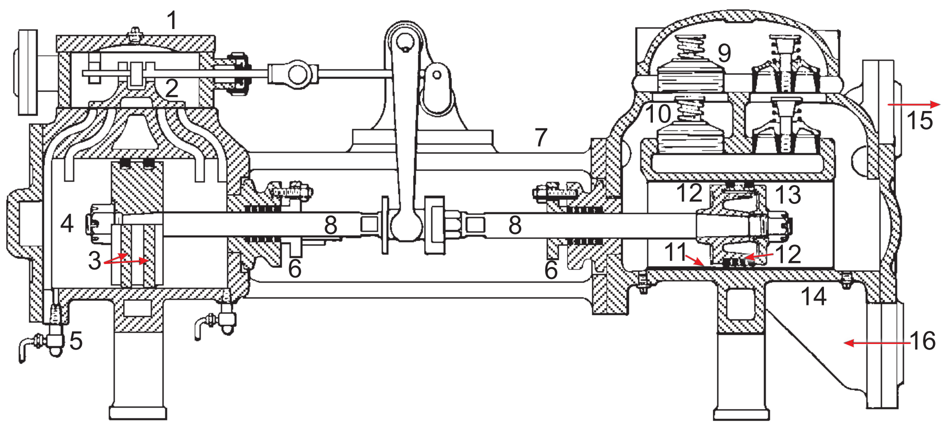


Figure 5 shows a reciprocating **duplex pump**, driven directly by a steam engine.

Figure 5 – Horizontal Duplex Pump Cross-Section



(a)



1. Steam chest
2. Slide valve
3. Piston rings
4. Steam cylinder
5. Drain cock
6. Stuffing box
7. Cradle
8. Piston rod
9. Discharge valve
10. Suction valve
11. Liner
12. Packing ring
13. Liquid piston
14. Liquid cylinder
15. Discharge outlet
16. Suction inlet

(b)

(Courtesy of Worthington Corporation)

Steam Engine Operation

Starting a Steam Engine

1. Ensure that all tools have been removed from around the engine, so that they do not cause any damage. Flywheels, pulleys, drive belts, and other moving parts need to be clear and free of debris.
2. Ensure that the steam chest and cylinder drains are open so all water can be cleared from these areas.
3. Open drains on the steam line to empty it of water.
4. When water stops flowing through the drain valves, open the stop valve slightly (crack the valve open) until steam blows freely through the drains. Some steam will condense in the steam line and cylinder at first. More water will flow through the drains, after the valve is cracked.
5. Never open a steam valve suddenly. Otherwise, any water present in the steam line will drive violently along the pipes, and cause water hammer. This can result in ruptured pipes or fittings.

Inspection While Engine is Running

At regular intervals, inspect all steam engines and the machinery being driven (pumps, fans, compressors etc.). Examine all lubricators to make sure that they are filled to the correct level and feeding properly. Monitor all bearings temperature to ensure they are not too hot.

Frequent inspection is recommended depending on site-specific conditions. Inspect engines more often if heavily loaded. Pay special attention to bearings if running hotter than normal.

Know the sound of a normally running engine. Any change in the noise may be a warning that something is wrong. The ability to detect any change of sound, however slight, will often lead to the discovery of minor troubles. These troubles may become serious if allowed to continue without adjustments or repairs.

Chapter Summary

In this chapter, discussion included:

a) The difference between heat engines and prime movers, and
b) How work is produced in a steam engine by converting heat energy into mechanical energy.

The construction of steam engines was illustrated. The operation of the simple steam engine was described. These materials will help in understanding how other machines operate, including certain heat engines and prime movers.

Chapter 2

Steam Turbines

Learning Outcome

When you complete this chapter you should be able to:

Describe the construction and operation of steam turbines.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Describe the principle of operation and major components of a steam turbine.*
2. *Describe the lubrication and sealing of steam turbine shafts.*
3. *Describe how the rotational speed of a steam turbine is governed and controlled.*
4. *List the steps to follow in a typical steam turbine start-up and shut-down.*

Chapter Introduction

Several types of steam turbines are used in industry today. Power Engineers must be familiar with the operation and general construction of steam turbines.

This chapter will describe the general construction and operation of steam turbines and their auxiliaries. The illustrated figures and sketches will help to:

a) Identify the major parts of a steam turbine.

b) Explain the principles of lubricating and speed governing system operation.

As a Power Engineer, it is essential to be aware of the safety aspects in running or operating a steam turbine. The Power Engineer must understand how an overspeed trip device works to provide protection to personnel who are working around the steam turbine. In addition, the general steam turbine start up and shut down guidelines will help promote an understanding of steam turbine operations.

OBJECTIVE 1

Describe the principle of operation and major components of a steam turbine.

GENERAL DESCRIPTION

Steam turbines convert heat energy to mechanical energy. They do this by directing high velocity steam onto shaft-mounted disks with moving blades attached. The action of the steam on the moving blades produces shaft rotation. In most steam turbines, the steam flows in the axial direction (parallel to the shaft). With some turbines, the steam flows in the radial direction around the shaft.

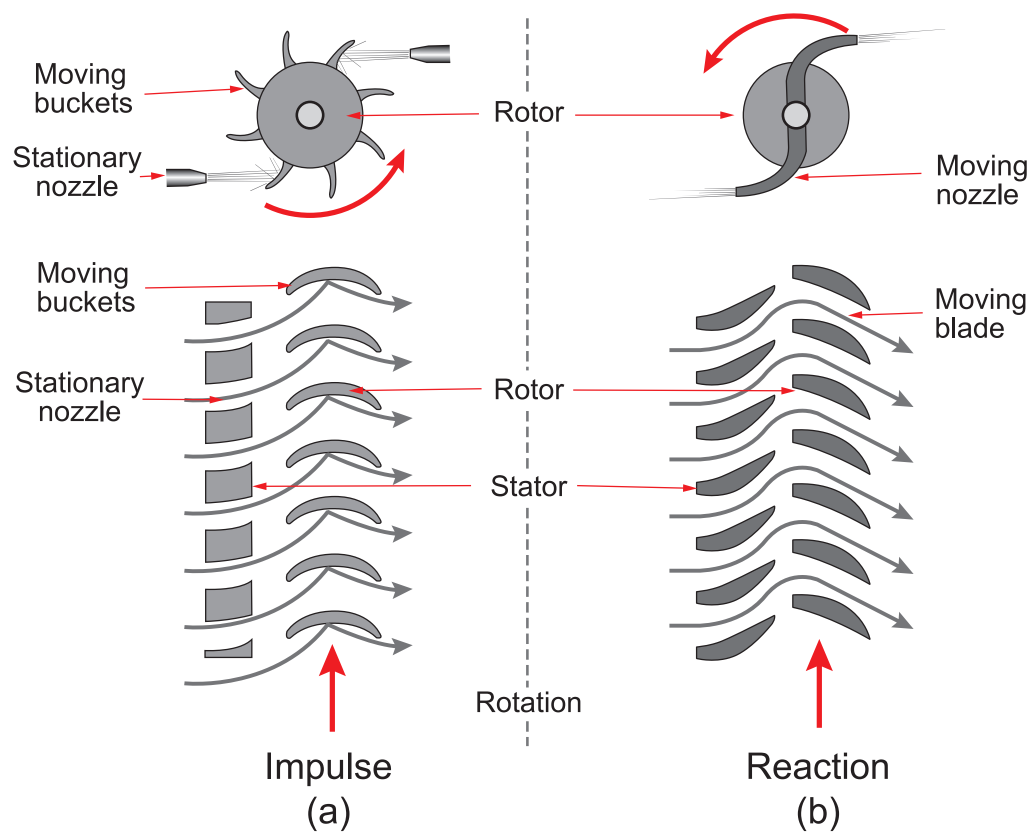
There are two basic types of steam turbines: **impulse** and **reaction**. They differ in how the steam expands through the turbine.

In the **impulse turbine**, high-pressure steam expands as it proceeds through stationary nozzles. This expansion and pressure drop creates jets of high velocity steam. In an impulse turbine, the drop in steam pressure only occurs in stationary nozzles.

When placed beside each other, both the stationary and moving blades of **reaction turbines** create steam passages shaped like bent nozzles. Therefore, in the reaction turbine, expansion and resulting pressure drop of the steam takes place through both the stationary nozzles and moving blades. However, the velocity increase of the steam takes place through stationary nozzles only.

Figure 1 shows the general arrangement of the steam nozzles and the blade wheel (**rotor**) of the basic design of impulse and reaction turbines.

Figure 1 – Impulse and Reaction Turbine Basic Designs



Stationary Passages (Stators)

The stationary passage of an impulse turbine consists of one or more stationary nozzles. These nozzles allow high-pressure steam to expand and convert some of its thermal energy into mechanical energy. The flow of steam exiting the nozzles, though reduced in pressure, travels at high velocity. The stationary nozzles direct the flow of steam onto the rotor blades. This transmits an impulse force to the moving blade when the steam jet flow strikes the moving blades and then changes direction.

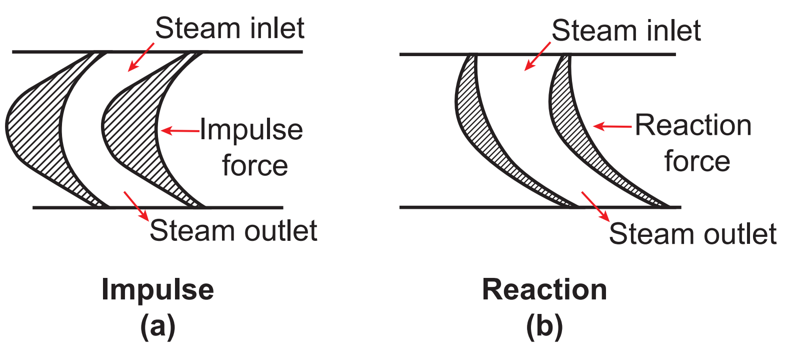
Reaction turbines use stationary nozzle-shaped blades to direct steam into moving nozzle-shaped blades, mounted on the rotor. Here, further steam expansion takes place and transmits a reaction force to the blades, causing them to rotate.

Rotor Passages (Rotors)

Blades (**buckets**) form the rotor steam-flow passages of impulse turbines, and serve to change the direction of the steam received from the stationary nozzles. Steam emerges from the stationary nozzles at a high velocity and strikes the moving blades. The moving blades absorb the velocity energy of the steam, and then redirect the flow of the steam.

Figure 2 shows the typical shape of impulse and reaction turbine blades when viewed in section.

Figure 2 – Impulse and Reaction Blades

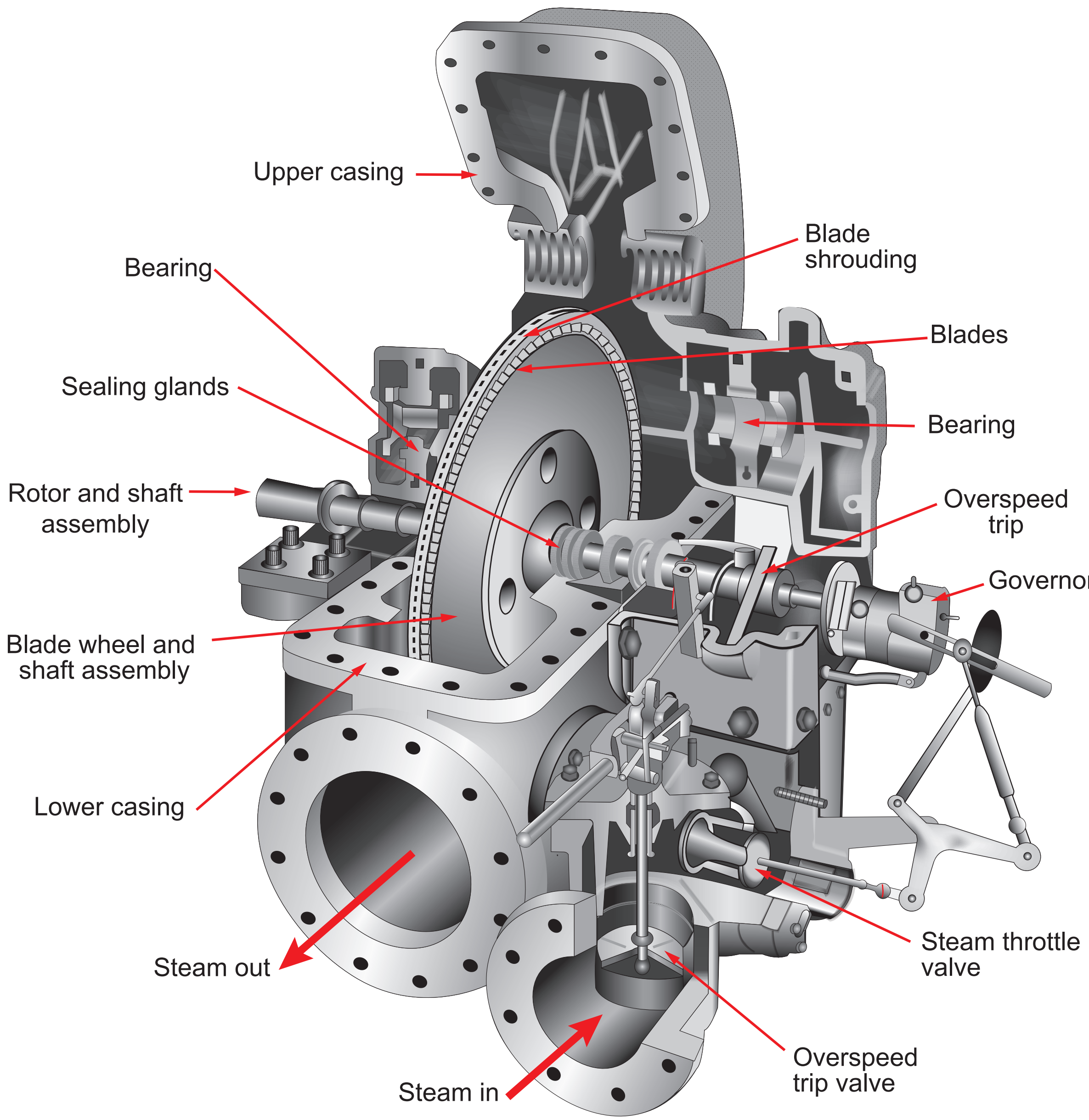


The impulse blades are shaped so that, when fitted into a blade wheel, the space between the blades does not allow any steam pressure drop as the steam passes through (other than a small loss due to friction). **Momentum** is the product of mass times velocity. **Impulse** is a change in momentum over a period of time. The thrust force created by the steam on the moving blades is due to the impulse of the steam as it changes direction (and therefore velocity) to follow the shape of the blades.

On the other hand, the reaction blades are specially sized and shaped to allow the steam pressure to drop. This produces a decrease in steam velocity and causes a reaction or back thrust on the blading. The effect is similar to that felt upon the nozzle of a fire hose when high-pressure water is issuing from the hose nozzle.

Figure 3 shows an "opened up" view of a small industrial single stage mechanical drive turbine.

Figure 3 – Mechanical Drive Turbine



The following gives a general description of some the essential steam turbine parts shown in Figure 3.

Bearings

The bearings shown in figure 3 are precision bored with high grade babbitt, have a split sleeve and oil ring (similar to the ring-oiled bearing). With the split sleeve design, the bearings can be removed without disturbing the wheel case cover. The bearing at the governor end serves as a combined thrust and journal bearing.

Sealing Glands

The **glands** consist of several segmental carbon rings, mounted adjacent to each other at either end of the shaft. Garter springs hold the carbon segments against the shaft. Because the carbon segments are located in individual grooves in the casing, they are free to move independently in a radial direction while maintaining contact with the shaft. This results in negligible leakage of steam from the wheel case along the shaft.

Rotor and Shaft Assembly

The rotor consists of a carefully machined and balanced forged steel disc, pressed over a key on a shaft. At the gland locations, the shaft is protected with a sprayed-on coating of stainless steel.

Blades

The blades are durable, rolled, and drawn stainless steel. They are securely held in machined slots in the wheel rim by drive screws.

Blade Shrouding

The inner and outer ends of the blades are stainless steel. The blade ends are shrouded to confine steam to the blade passage and to stiffen the blades against vibration.

Casing

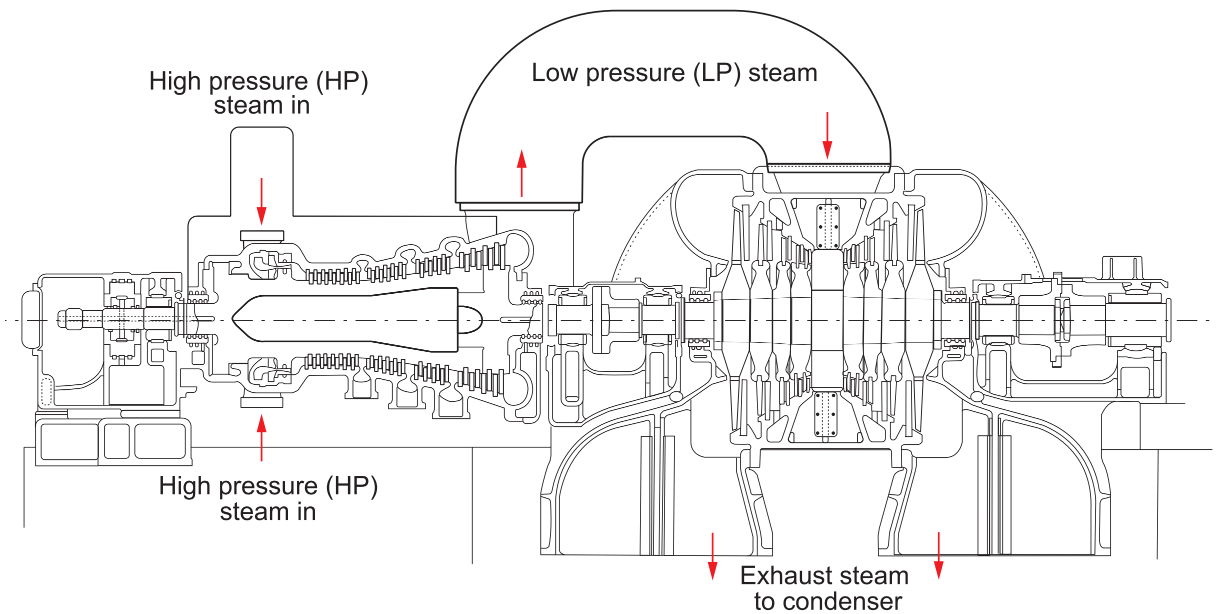
The top half of the casing may be removed without disturbing other parts or piping connections. There are no internal high-pressure casing joints; the casing is subject to exhaust pressure only. The casing has two exhaust openings so that the exhaust line may be connected at either side (only one side is shown in the diagram in Figure 3). A blind flange at the unused exhaust opening is used for wheel, blade, and nozzle inspection.

Most large steam turbines use a combination of impulse rotors and reaction rotors. The impulse rotors are at the front end where steam velocity is the highest. As steam moves through the impulse rotors, its velocity decreases while its pressure remains constant. As the steam moves into the reaction rotors, the velocity decreases while the pressure reduces in each moving rotor wheel.

The reaction rotors are progressively larger in diameter, and take advantage of the energy of the steam at reduced pressure and increased volume. Figures 4(a) and 4(b) show the high- pressure (HP) and low-pressure (LP) sections of a 66 MW turbine designed to operate with steam conditions of 6000 kPa and 425°C.

Figure 4 – Multi-Stage Steam Turbine

(a)



(b)

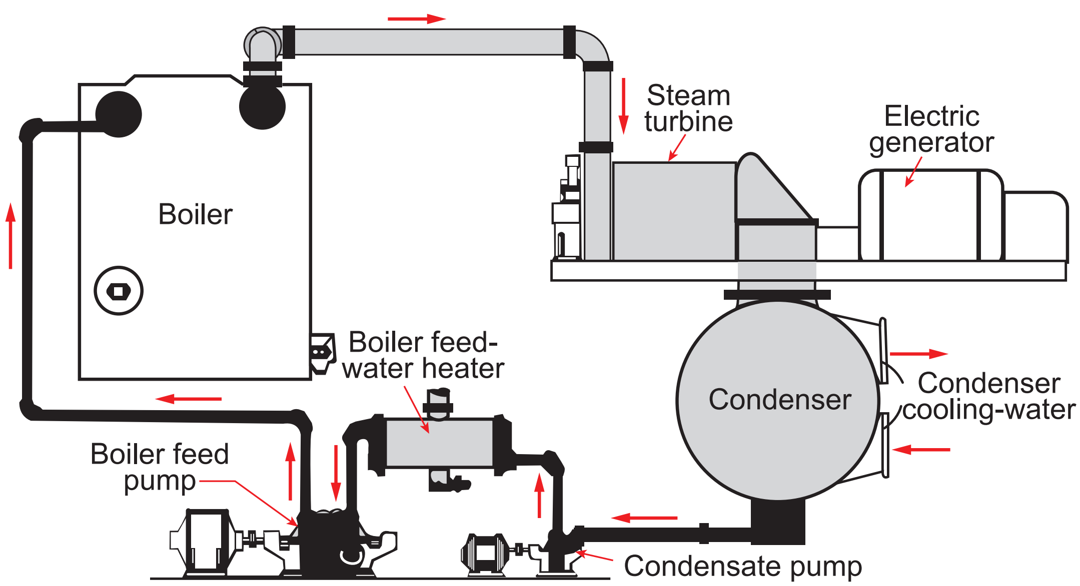
Steam is generated in the boiler at high pressure and superheated to a high temperature. The steam flows through the turbine to develop mechanical power to drive a piece of equipment, such as an electrical generator. Then, the steam is exhausted from the low-pressure turbine to a **condenser**. The cooling water in the condenser transforms the steam back into water (condensate). The condensate is removed from the condenser by a pump, discharged to boiler feedwater heaters, and then moves to a boiler feed pump. This pump raises the pressure above the boiler pressure to enable the water to return to the boiler and continue the cycle.

The condenser serves two important functions in condensing the steam:

1. The high vacuum that is produced increases the pressure drop in the turbine, and produces more work and a higher degree of efficiency.
2. The condensate provides a clean source of boiler feedwater.

Figure 5 shows the steam cycle through a simple steam power plant.

Figure 5 – Simple Power Plant Cycle



Objective 2

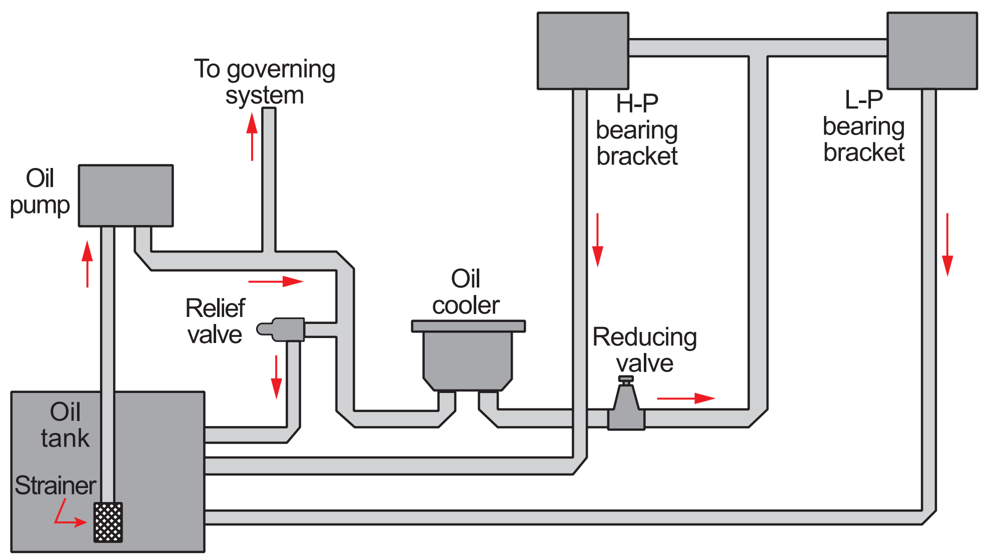
Describe the lubrication and sealing of steam turbine shafts.

Lubrication

Generally, more lubricating oil is supplied to the turbine bearings than that required simply for lubrication. The purpose of this excess supply is to carry away the heat conducted along the shaft from the steam space, and to maintain the bearings at a safe working temperature.

A lubricating oil system is shown in Figure 6. The oil pump is gear-driven from the main turbine shaft, and supplies oil, under pressure, for positive bearing lubrication. From the oil pump, the high pressure oil branches off to the governing system for turbine speed regulation. The relief valve located between the oil pump and the oil cooler protects the oil pump and piping from overpressure. The remaining high-pressure oil passes first through an oil cooler and then to a pressure reducing valve (PRV) to reduce oil pressure suitable for bearing lubrication. The lubricating oil then feeds through of the high-pressure (H-P) and low-pressure (L-P) bearings, then returns back to the oil tank to start the cycle again.

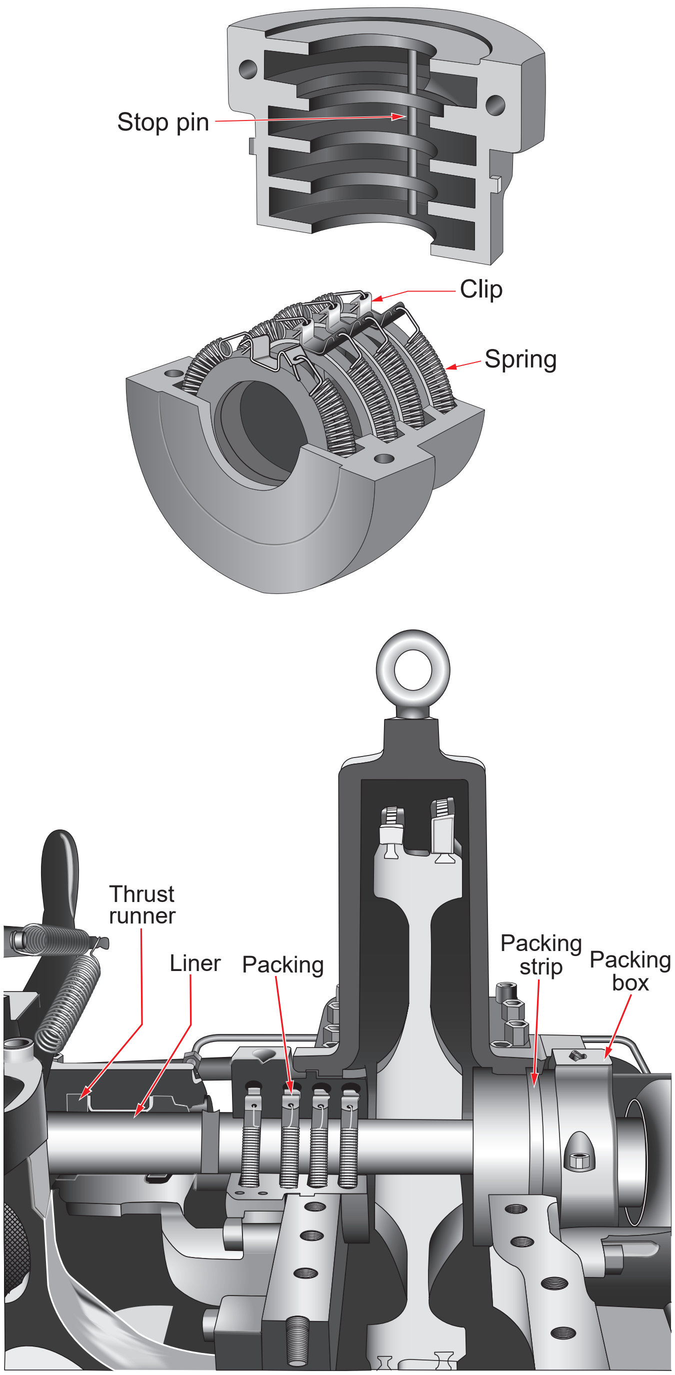
Figure 6 – Schematic Diagram of Turbine Lubrication System



Carbon Sealing Rings

Small turbines (as in Figure 3) will generally use carbon sealing rings for shaft sealing. Figure 7 shows segmental carbon sealing rings for the steam glands on the turbine shaft. Steam-tight glands are necessary on turbine shafts to restrict the flow of steam from the steam space along the shaft to the atmosphere. The tight radial clearance prevents steam leakage along the shaft. Steam pressure exerted on the face of the carbon segments pushes them against their seats in the casing grooves. This prevents steam leakage around the outside of the ring.

Figure 7 – Carbon Sealing Rings and Packing Glands



Shaft openings at both ends of the turbine casing must be sealed. The sealing rings may be held in the casing seal glands bolted to the casing (Figure 7). These glands are inserted in the casing and split on the horizontal centerline.

The carbon rings consist of three segments. The outer surface of each ring is grooved to accept a **garter spring**, which keeps the assembled segments together and holds the segments to the shaft. Spring pressure holds the packing in place axially, but permits slight radial movement for automatic concentric alignment with the shaft (Figure 7).

The carbon sealing rings contain graphite and are self-lubricating. Shafts have **Monel metal** sprayed at the carbon packing seal area to minimize corrosion.

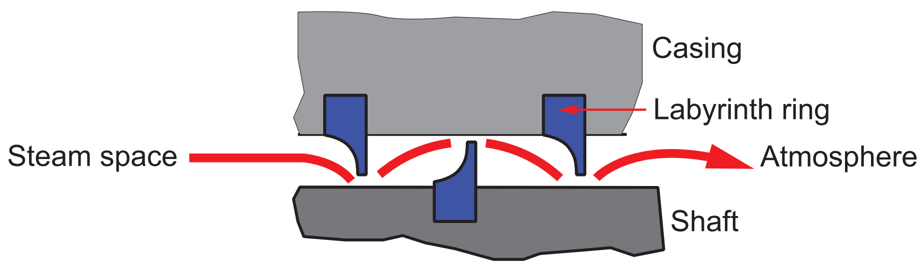
Labyrinth Glands

High output machines, which operate with high temperature and high-pressure steam, usually employ **labyrinth glands** to prevent the escape of steam along the shaft. A labyrinth gland, as the name implies, offers a very narrow and winding path to the steam.

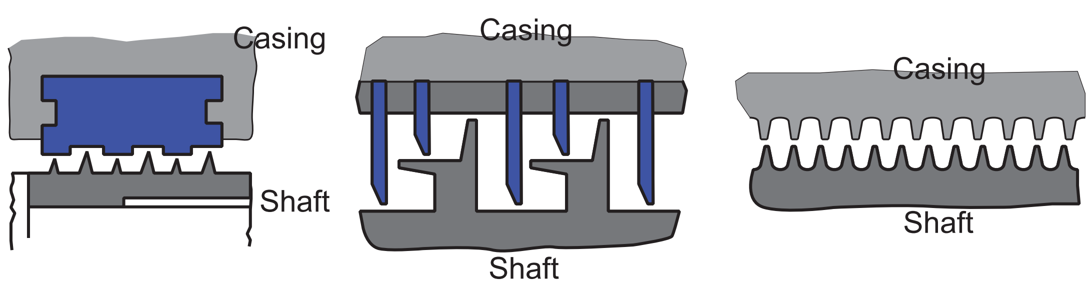
Figure 8 shows cross-sections of labyrinth glands. The clearance between the turbine shaft and casing kept as narrow as possible. Any steam escaping through this narrow clearance immediately reduces in pressure. A number of subsequent pressure drops is sufficient to restrict the steam leakage to atmosphere, even of high-pressure steam, to a very small amount.

Figure 8(a) shows a section of turbine shaft with one labyrinth ring mounted on the shaft and a section of turbine casing with two labyrinth rings mounted in the casing. Steam attempting to escape from the turbine steam space to atmosphere forced to pass through three narrow gaps on its way out. Figure 8(b) shows further variations on the basic idea shown in Figure 8(a).

Figure 8 – Labyrinth Glands



(a)



(b)

Objective 3

Describe how the rotational speed of a steam turbine is governed and controlled.

Turbine Governing

The **governor** is a key component of a steam turbine. It automatically regulates the speed and power output of the turbine at various load conditions. To do this, the governor automatically controls the steam flow through the turbine by adjusting the steam control valve. As a turbine load increases, it slows down. The governor responds by admitting more steam to the turbine nozzles. As a turbine load decreases, the turbine speeds up. The governor responds by decreasing the amount of steam admitted to the turbine nozzles. Many governors work by sensing the turbine shaft speed, and then positioning a governor valve by a variety of mechanical means.

Most turbine governors are mechanical or mechanical-hydraulic. The following are two types of governing system:

1. Fly weight governing system
2. Oil pump governing system

Flyweight Governing System

Flyweight governing systems can be either purely mechanical or mechanical-hydraulic systems. In both cases, revolving weights (**flyweights**) move in accordance to changes in turbine speed. The change in the flyweight position will change the governor valve position, which will then change the steam flow to the turbine.

In the case of a purely mechanical governor, the flyweights apply force to the steam governor valve directly or indirectly, using only mechanical means. In the case of a mechanical hydraulic governor, the flyweight assembly acts upon a **hydraulic relay** that varies the hydraulic pressure used to position the governor valve. In both cases, the governor valve changes the turbine steam supply in accordance to changes in load.

Figure 9 shows a typical pair of governor flyweights. The rotation of the turbine shaft makes the flyweights spin, via a worm drive. Increase in speed causes the flyweights to move outwards due to centrifugal force. Decrease in speed causes them to move inward. For every turbine speed, the flyweights take on a definite position.

When turbine speed increases, the flyweights compress a spring until the increased spring force balances the flyweight force. The governor sleeve, which moves independent of the flyweight drive system, then moves upward. The opposite occurs with a decrease in turbine speed.

Figure 9 – Governor Weights

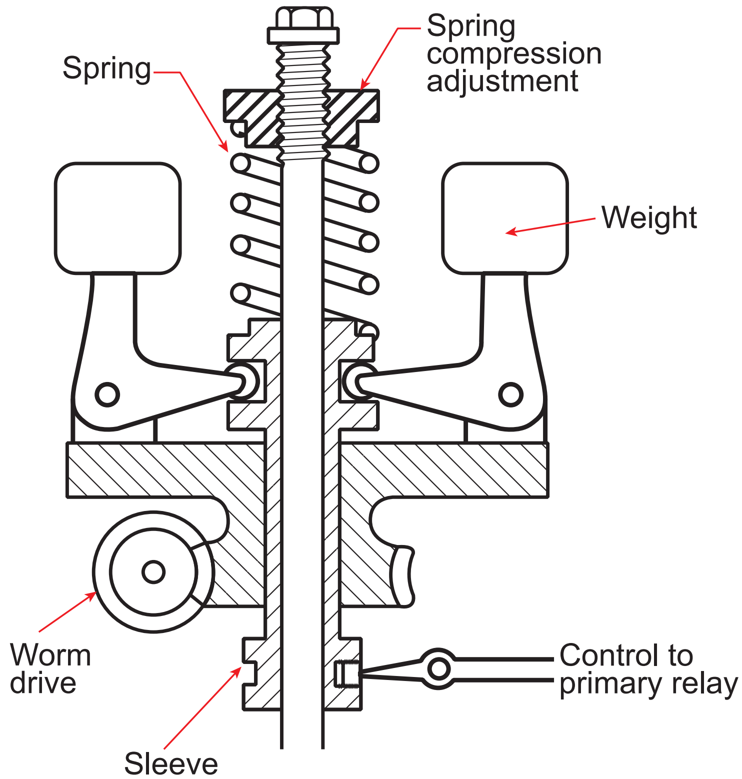


Figure 10 shows a flyweight-operated oil relay governing system. As the speed of the turbine spindle (the end of the turbine shaft) increases, the flyweights spin faster and push out against the governor springs. This moves the governor sleeve to the "fast" position, and raises the **pilot valve** via the floating lever. The result is that high-pressure hydraulic oil flows from the pilot valve to the top of the relay piston, and closes the throttle valve. Closing the throttle valve reduces the steam supply and prevents further increase in turbine speed.

The throttle valve does not close completely, though. Changes in the position of the throttle valve also change the position of the pilot valve via the floating lever. Closing the throttle valve lowers the pilot valve and shuts off the oil flow to the relay piston, to stop further movement of the throttle valve.

As the speed of the turbine decreases, the weights spin more slowly and lower the governor sleeve. This lowers the pilot valve, allows oil to flow below the relay piston, and raises the throttle valve. Raising the throttle valve increases the steam supply and turbine speed.

The throttle valve does not open completely, though. Opening the throttle valve raises the pilot valve and shuts off oil flow to the relay piston to stop further movement of the throttle valve. Therefore, for every turbine load, there is a definite turbine speed and a definite throttle valve position.

A manual ("hand") speed control, called a **speeder** handwheel, allows adjustment of the turbine speed when running on load.

Figure 10 – Oil Relay Governor Gear – Mechanical-Hydraulic Governor

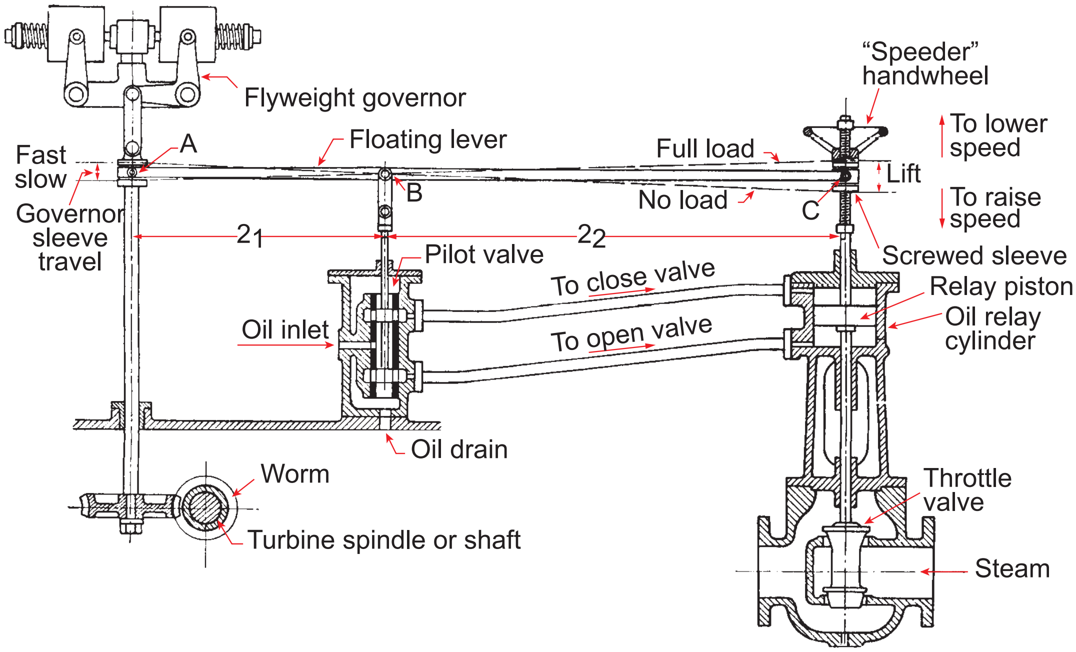


Figure 11 – Schematic Drawing of Hydraulic Governing System

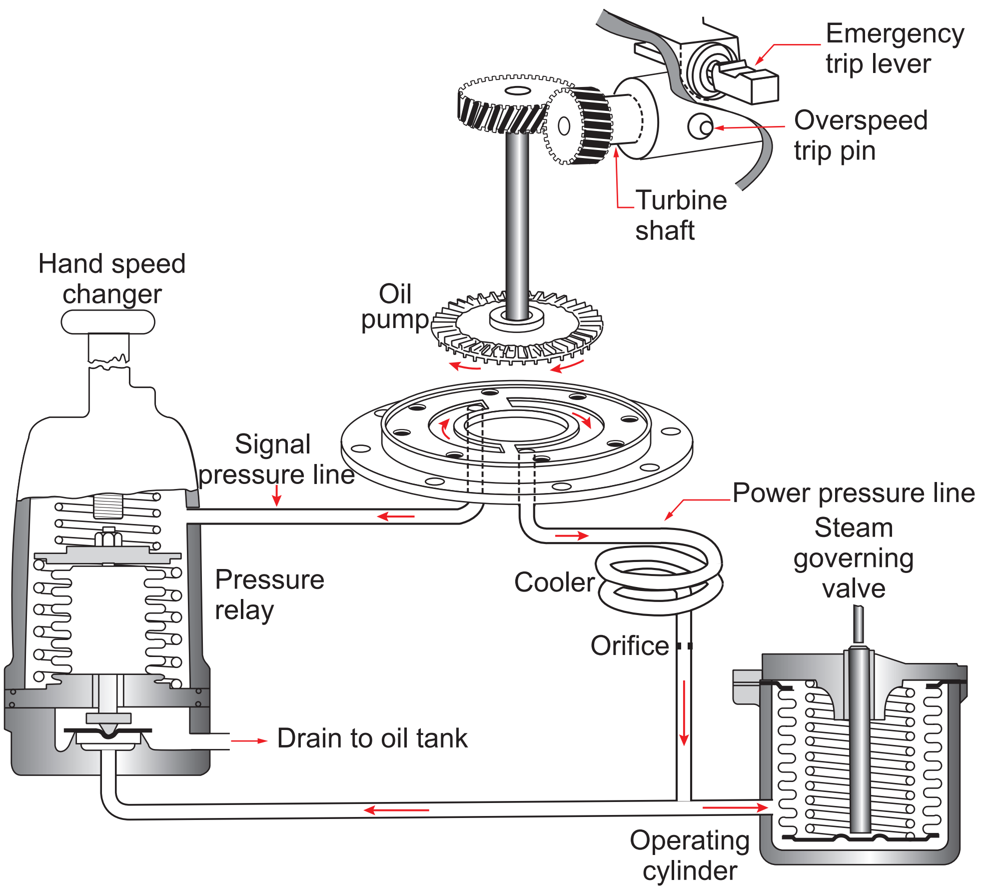


Figure 11 shows a hydraulic turbine governing system. This system has no flyweights. Instead, it uses an oil pump that varies in output pressure with turbine speed. The governor oil pump is gear-driven by the turbine shaft to supply hydraulic oil through two passages to the pressure relay.

One passage leads directly to the pressure relay via the signal pressure line; it provides an oil pressure signal that varies with the turbine speed. The other passage supplies oil through an orifice to the operating cylinder of the steam governing valve, and to the underside of the pressure relay via the power pressure line.

The signal pressure and power pressure oppose each other across the pressure relay. The diaphragm and spring forces of the pressure relay are normally in equilibrium. The hand speed changer adjusts the spring compression. The spring setting determines the speed of the turbine.

Under steady load conditions, the oil pump sends oil to the pressure relay and the operating cylinder. Oil continually bleeds from the operating cylinder through the pressure relay drain valve and returns to the oil tank. Despite the oil bleed, a constant oil pressure exists downstream of the orifice to keep the force on the operating cylinder bellows constant. The pressure remains constant because the bled oil is replenished to the operating cylinder, through the orifice, at the same rate at which it drains to the oil tank. Therefore, the operating valve stem does not move and the steam valve stays in a constant position.

If the turbine load increases, the turbine speed decreases. This causes an immediate pressure decrease on top of the pressure relay, and a delayed pressure decrease in the operating cylinder. (The orifice delays the pressure decrease in the operating cylinder.) When the pressure drops in the pressure relay, the spring forces the oil drain to open further, and bleeds oil from the operating cylinder. This reduces the pressure in the operating cylinder. The spring in the operating cylinder then positions the operating valve stem to open the steam admission valve. Eventually, enough oil bleeds through the orifice to hold the operating valve stem at its new position. The opposite sequence occurs on a decrease in turbine load.

The governing valve and trip-throttle valve are combined in the same assembly. The trip throttle valve controls steam admission to the turbine on startup, and shuts off all steam in case of an overspeed trip.

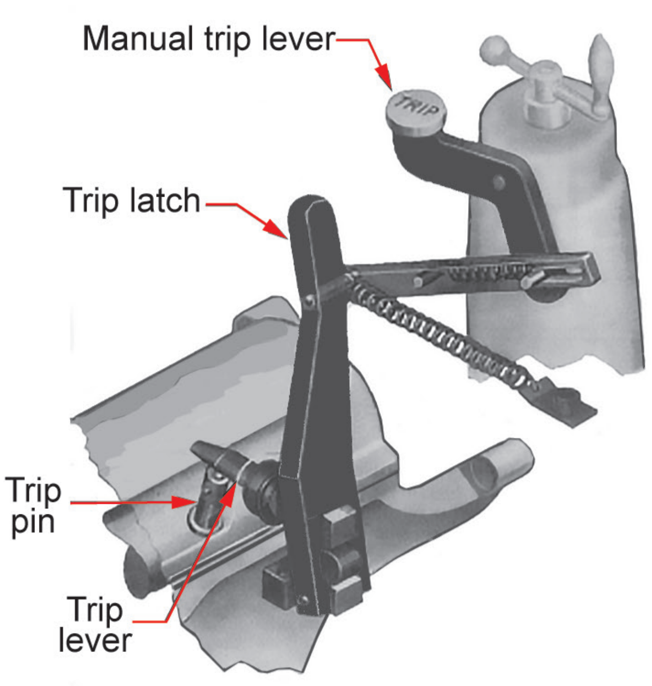
Overspeed Trips

Turbines are designed to withstand the centrifugal forces present when running at all speeds up to their specified maximum. A sudden loss of load, however, can cause an unprotected machine to increase in speed to where centrifugal forces produced can tear the blades from the blade wheels. This outcome can result in a catastrophic wreck of the turbine with considerable risk of injury to operating personnel. Therefore, turbines must be protected against rotating at excessive speed.

An **overspeed trip** mechanism protects the turbine against this danger. Most designs rely on centrifugal force to release some catch, which in turn, closes the steam supply valve.

Figure 12 illustrates a typical overspeed trip mechanism used on a small mechanical drive steam turbine. The primary element that senses overspeed is a spring-loaded unbalanced weight mounted in the turbine shaft, called the **trip pin** (also called an **overspeed bolt**) (Figures 12 and 13).

Figure 12 – Turbine Overspeed Trip Mechanism



(Courtesy of General Electric)

Figure 13 – Turbine Shaft, Showing Trip Pin

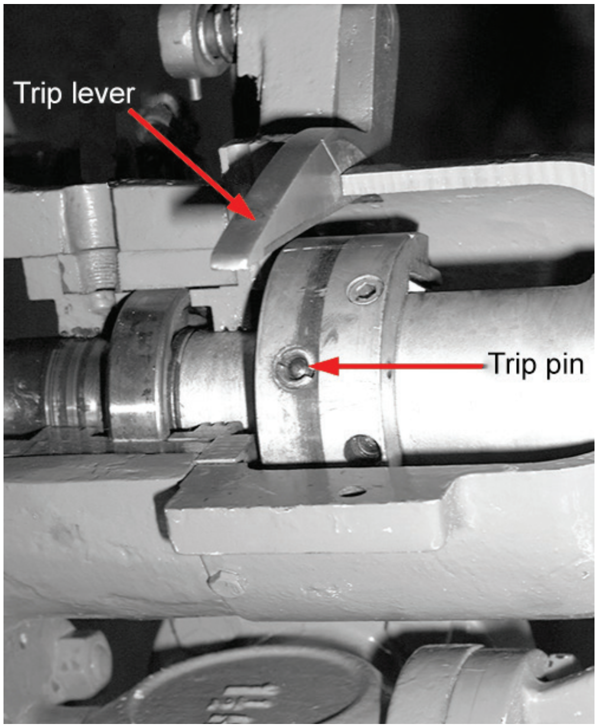
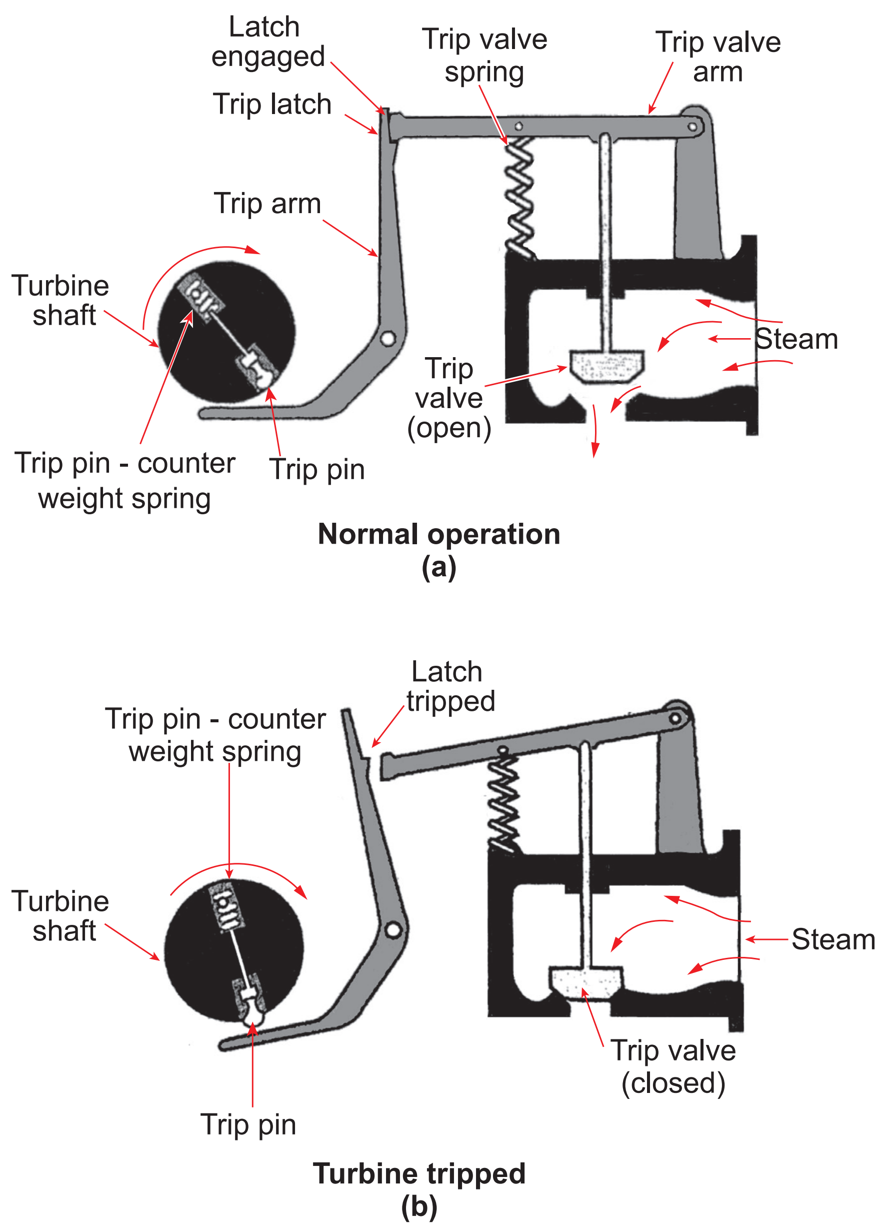


Figure 14(a) shows the turbine overspeed trip system in normal operation. Steam enters the turbine and turns the shaft, where the trip pin counter-weight is mounted. At this time, the "Trip Valve" is open with the trip valve arm engaged to the trip latch.

In Figure 14(b), if the rotational speed of the turbine shaft increases to trip speed, the excessive centrifugal force it generates will cause the trip pin to overcome the force of the counter-weight spring. This action moves the trip pin outward to strike against the trip latch lever. This will cause it to disengage from the trip valve arm to close the trip valve, and shut off all steam to the turbine.

Figure 14 – Turbine Overspeed Trip System



Objective 4

List the steps to follow in a typical steam turbine start-up and shut-down.

Note: The following instructions apply to a small non-condensing steam turbine used for driving a boiler feedwater pump. Only competent and qualified operators should start or stop a steam turbine or a feed pump. Always consult and follow site-specific and manufacturer start up and shutdown instructions.

Starting or stopping pumps and turbines must only be performed under the direction of the shift engineer or control room operator.

General Instructions for Starting a Small Steam Turbine Driving a Feedwater Pump

The steps below are a general procedure for starting a small non-condensing steam turbine driving a feedwater pump.

1. Prepare the feedwater pump.
   a) Clear any lockouts or tagouts on the pump being started, to ensure it is safe to operate.
   b) Check the area surrounding the pump for rags, tools, or other materials that may hamper the operation of the pump.
   c) Check the bearing lube oil levels and add oil, if necessary.
   d) Start bearing cooling water, if applicable.
   e) Close the pump casing drains and prime the pump.
   f) Conduct a valve line-up. The suction valve must be open. Centrifugal pumps are often started with the discharge valve shut.
   g) Open the pump warm-up line to circulate hot boiler feed through the pump to warm it up. A pump may also be warmed up when priming the pump, by permitting hot water from the pump inlet to flow through the pump vent and/or its drain.
2. Prepare the steam turbine.
   a) Clear any lockouts or tagouts on the turbine being started, to ensure it is safe to operate.
   b) Check the area surrounding the turbine for rags, tools, or other materials that may hamper the operation of the turbine.
   c) Check the bearing and governor lubricating oil and add oil, if necessary.
   d) Start the lube oil cooling water, if applicable.
   e) Check the valve line up. This may include:
      i) Turbine steam inlet and exhaust valves are closed.
      ii) Steam leg drain is open, steam trap bypasses are open, and steam trap is in service.
      iii) Turbine casing drains are open, steam trap bypasses are open, and casing drain steam traps are in service.
   f) Reset the overspeed trip.

3. Ensure the steam header is at operating pressure.
    a) Slowly warm up the steam line to the turbine.
    b) When the steam leg is blowing steam, close the manual drain and trap bypasses.
    c) Leave the steam trap in service.
4. Warm up the turbine.
    a) Fully open the exhaust valve. Ensure condensate blows from the casing drain.
    b) Allow the turbine to warm slowly until only steam is blowing form the casing drain.
    c) Close the drain valve or trap bypass. Ensure the casing drain trap remains in service.
5. Open the steam inlet valve slightly to start the turbine rolling.
6. While the turbine is on a slow roll, check and ensure:
    a) All bearings are receiving proper lubrication.
    b) The cooling system is at proper temperature ranges.
7. When the turbine is properly warmed up:
    a) Raise the turbine speed gradually by opening the steam inlet valve fully.
    b) Ensure the governor takes over control of the turbine speed. **NOTE:** Turbines that drive pumps may have governors that vary the speed of the turbine in order to maintain the discharge pressure setpoint.
8. Manually test the overspeed trip.
    a) Ensure the turbine stops.
    b) Close the steam inlet to the turbine.
    c) Reset the overspeed trip.
9. Restart the turbine, following steps 5, 6, and 7.
10. Gradually open the boiler feed pump discharge valve fully.
11. Once the feedwater pump is on-line and fully functioning, perform post start-up checks:
    a) Check lube oil level, flow, pressure, and temperature.
    b) Check and adjust cooling water flow.
    c) Observe unusual noises, vibrations, or odours.

General Instructions for Stopping a Small Steam Turbine Driving a Feedwater Pump

Once again, the steps below are a general procedure only. It is critical to follow the manufacturer's instructions and site-specific procedures when stopping a pump or turbine.

1. Gradually reduce feedwater pump load.
2. Manually test the overspeed trip.
3. Close turbine steam inlet and exhaust valves completely.
4. Open the steam leg and casing drains.
5. Open steam trap bypasses.
6. Isolate both inlet and outlet valves of the feedwater pump.
7. Turn off cooling water to the pump and turbine lube oil systems.

Chapter Summary

This chapter covered the main aspects of steam turbines, such as:

- The two main varieties of steam turbines and their operating principles,
- Basic steam turbine construction,
- Fundamental steam turbine components, and
- Small turbine operation.

This included examination of lubrication systems, governor systems, and gland sealing systems. As well, turbine start-up and shut-down were covered. Finally, the chapter stressed that only qualified operators, following accepted procedures, must start or stop turbines. Other chapters examine more fully how steam turbines fit within and rely upon other power plant systems.

CHAPTER 3

Condensers and Cooling Towers

Learning Outcome

When you complete this chapter you should be able to:

Describe the operation and maintenance of condensers and cooling towers.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Explain the construction and operation of condensers, and how they relate to the operation of cooling towers.*
2. *Explain the principle of operation, the purpose, and the major components of cooling towers.*
3. *Describe the construction and operation of natural draft cooling towers.*
4. *Describe the construction and operation of mechanical draft cooling towers.*
5. *Discuss cold climate operation for cooling towers.*
6. *Explain typical problems and resolutions required within the operation of cooling towers.*

Chapter Introduction

Condensers and cooling towers are common to many power plants. Many plant processes, including refrigeration, power generation, smelting, and refining, develop large amounts of heat. This heat must be removed to permit equipment and processes to continue operating. Heat, therefore, must be removed from the source of heat production, and rejected to a large heat sink.

Condensers reject latent heat, by converting a fluid from its gaseous to its liquid state. They reject heat to the atmosphere, large bodies of water, or cooling towers.

Cooling towers accept heated coolant from condensers and other heat exchangers, and then reject that heat to the atmosphere. They do this by evaporating a portion of recirculated cooling water. Among their many applications, cooling towers are used where there is a need to condense refrigerant vapour, condense exhaust steam, cool internal combustion engines, and cool lubricating oil.

This chapter covers the application and operation of condensers and cooling towers in industry. Particular attention is paid to power plant applications.

Objective 1

Explain the construction and operation of condensers, and how they relate to the operation of cooling towers.

Condensers are heat exchangers that come in many forms. They are commonly used to condense steam into water, for re-use as boiler feedwater. In refrigeration systems, condensers convert hot refrigerant gas to liquid, for re-use in evaporators.

In steam plant use, condensers also help reduce backpressure on steam turbines. More energy can be extracted from a steam turbine that exhausts into a vacuum than one exhausting against backpressure.

The largest heat exchanger in the steam plant is the condenser. It condenses the turbine exhaust steam back to water, which returns to the boiler as feedwater.

Principle of Operation

The primary purpose of a **condenser** in a steam power plant is to improve the efficiency of the turbine. It produces and maintains a vacuum at the turbine exhaust, allowing the steam to expand to a lower pressure. This allows the turbine to recover more of the heat energy from the steam and, therefore, do more work per kilogram of steam.

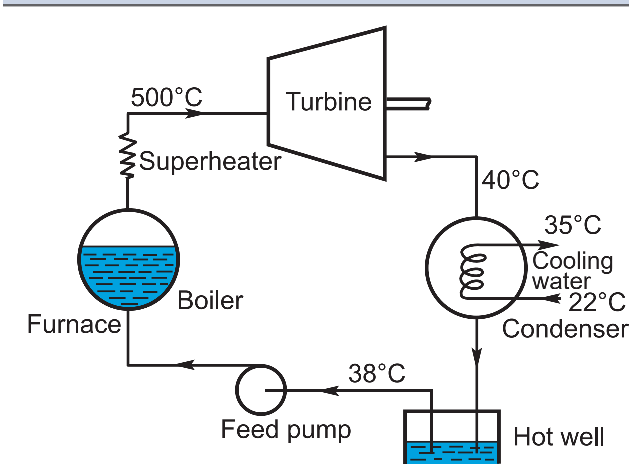
A secondary purpose is to recover steam and convert it to condensate. The recovered condensate can be returned to the boiler as feedwater. This reduces the demand on the feedwater treatment processes.

A third purpose is to remove air and other non-condensable gases from the steam/condensate. This reduces their concentration in the systems downstream of the turbine and condenser. In effect, the condenser acts like a deaerator.

Simple Condensing Steam Cycle

A large percentage of the electricity generated in the world is produced in power stations using generators driven by condensing steam turbines. Figure 1 is a simple diagram of the steam cycle in such a plant. The boiler burns fuel to generate steam. The turbine converts the energy in the steam into mechanical work.

Figure 1 – Simple Steam Plant Cycle



Condensing the steam is the largest single heat loss in the steam cycle. This is because the latent heat of the steam entering the condenser transfers to the cooling water, and then dissipates into the atmosphere via a **cooling tower.**

Condensing the steam must occur at the lowest practical pressure. This enables the turbine to extract the maximum amount of work from the steam. To achieve this, the condenser must be capable of maintaining a vacuum in the region of 710 mm mercury or 6.9 kPa abs, while handling a full load of exhaust steam from the turbine. The condenser will do this most efficiently if only the latent heat is removed from the steam. This means the condensate temperature should be as close as possible to the steam temperature. Further, the cooling water circulating through the condenser is used most efficiently when the difference between its exit temperature and the steam inlet temperature is at a minimum.

Adding a condenser can increase the efficiency of a turbine by 50%. If the exhaust steam can be used for heating or process work, the overall plant efficiency is even higher. Typical thermal efficiencies are:

- 20% when exhausting to atmosphere
- 30% when condensing
- 80% or more when the exhaust steam is used for heating or process work

Condenser Types

Condensers can be divided into two main groups: contact and surface. Both condenser types can be subdivided. Each type has a specific application.

Contact condensers, also called **jet condensers**, operate by bringing exhaust steam and cooling water into direct contact with each other. The steam mingles with the cooling water, condenses, and the condensate leaves the condenser with the cooling water.

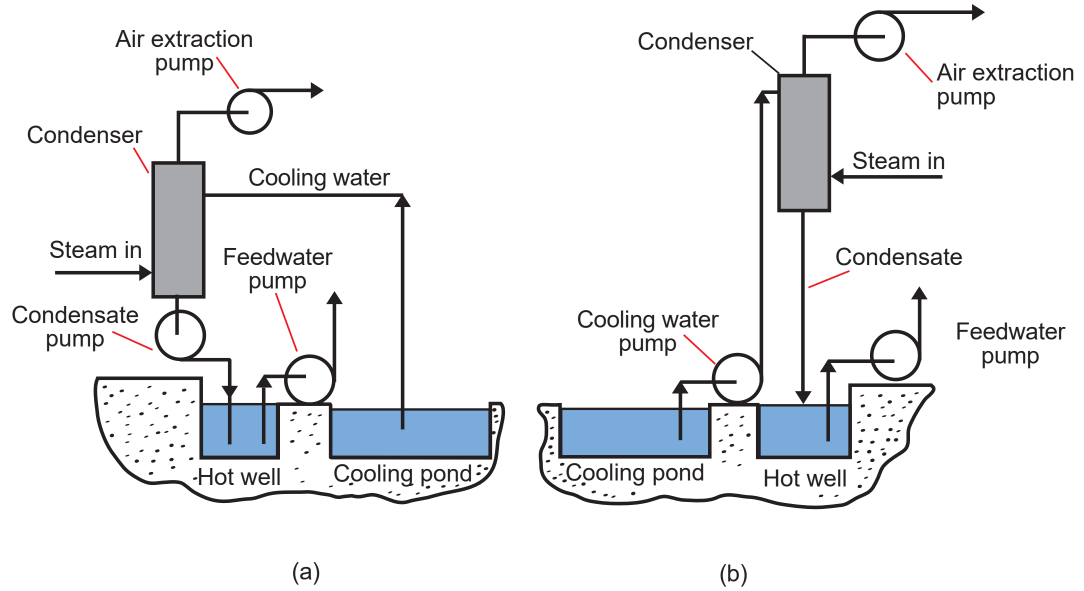
Direct contact condensers have a distinct disadvantage. They require the cooling water to be chemically treated to avoid contamination of the condensate and thus maintain acceptable feedwater purity. For this reason, there are relatively few direct contact condensers in service.

Figure 2 shows two varieties of contact condenser. In 2(a), the steam enters the condenser vessel and condenses, forming a vacuum. This vacuum is powerful enough to draw cooling water from the cooling pond. Because the condenser is under vacuum, the condensate must be pumped out of the condenser and into a storage area called a **hot well**. The boiler feedwater pump draws directly from the hot well, and returns the water to the boiler.

Figure 2(b) shows a 'barometric" condenser. In this situation, the condenser is kept high enough (the height of a barometric head of water) above the hot well that condensate flows to the hot well unaided. For this system to work, cooling water must be pumped into the condenser from the cooling pond.

Both condensers are equipped with extraction pumps, to remove air and non-condensable gases that accumulate in the condenser. These undesirable gases increase backpressure on the turbine, and reduce plant efficiency.

Figure 2 – Types of Contact Condensers

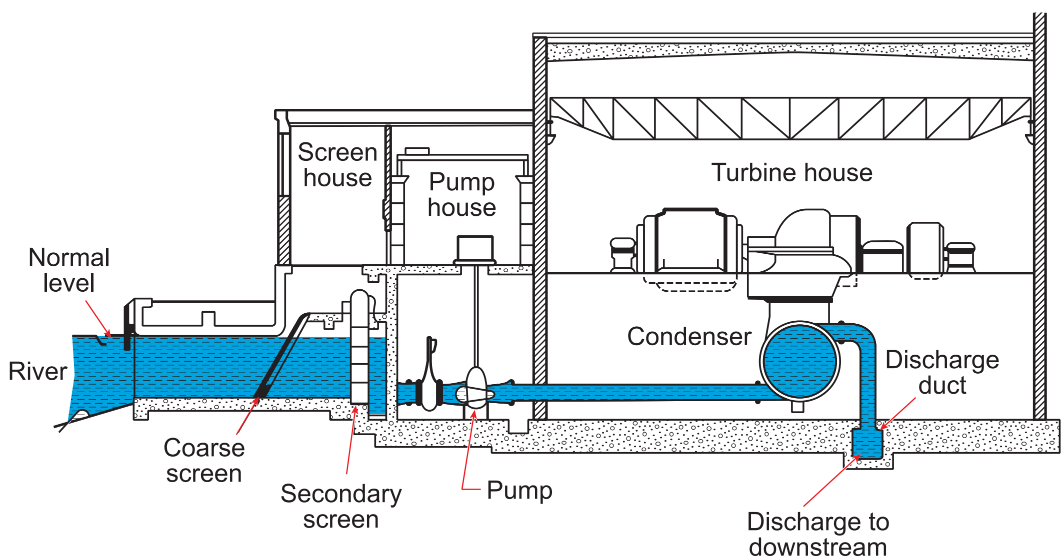


Surface condensers are far more common. They have a barrier to prevent contact between the exhaust steam and the cooling medium. The cooling medium may be water or air. Heat is transferred from the steam, through the separating surface to the cooling medium.

In the case of a water-cooled condenser, the cooling water is pumped through small diameter tubes. The exhaust steam flows over and around these tubes. The condensate is collected from the bottom of the condenser shell.

Figure 3 shows an arrangement of a surface condenser, located at the exhaust of a steam turbine.

Figure 3 – Surface Condenser

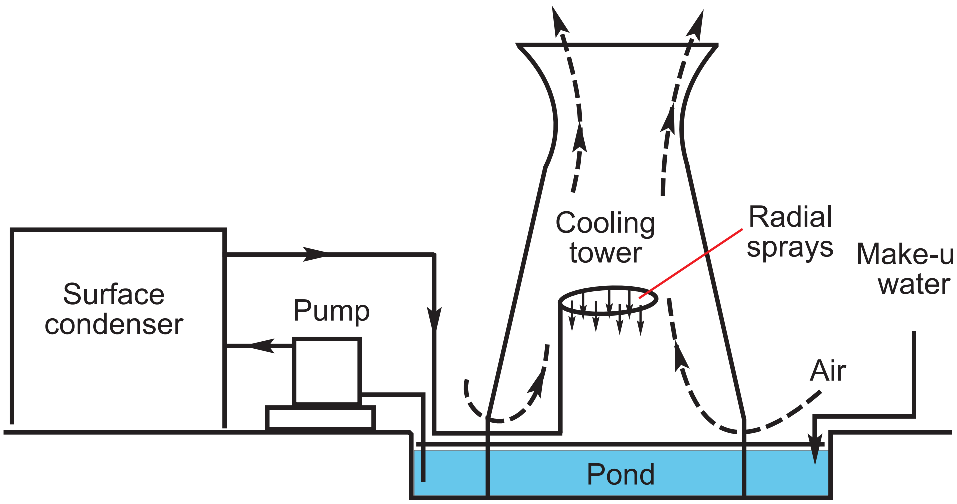


In a water-cooled condenser, the heat transfer surface is a collection of tubes located in the condenser shell. The cooling medium (water) flows through the tubes. Steam occupies the shell, and surrounds the outside surface of the tubes. Cooling water, if sourced from a river, lake, or other body of water, cools naturally before being pumped through a condenser.

After gaining heat in the condenser, the cooling water is simply discharged back into the body of water downstream of the water intake. Environmental regulations permit only a small temperature rise in the cooling water before it is reintroduced to the body of water. Higher temperature water could cause ecological problems such as high algae or bacterial counts, or water that is too warm for native fish to live and breed. The exact permissible discharge temperature range will be stipulated in the plant's environmental license.

When a reusable supply of cooling water is used, the water must be cooled after absorbing heat in the condenser. Figure 4 shows a system that incorporates a cooling tower for this purpose. The "hot" cooling water outlet from the condenser passes through the cooling tower, which uses water sprays and evaporation to remove heat from the cooling water. The cooled water drops into a pond. From there, it is again pumped through the condenser. Smaller systems may use a smaller design of cooling tower. They may also use overhead aerial, fan type coolers.

Figure 4 – Condenser using Cooling Water from a Cooling Tower



Objective 2

Explain the principle of operation, the purpose, and the major components of cooling towers.

Cooling towers take heated water and reduce its temperature for re-use as a coolant. The circulated water is referred to as cooling water (CW).

Principle of Operation

Heated cooling water is pumped to the top of a cooling tower. The water is distributed in the tower by spray nozzles and splash bars. This exposes a very large water surface area to atmospheric air, aiding evaporation. Dry atmospheric air circulates through the cooling tower, warms up, and carries away warm humid air, leaving the remaining water cool. One of the following methods is usually used to circulate the air:

- Fans
- Convection currents
- Natural wind currents
- Induction effects from the water sprays.

Most of the temperature increase of the air (and the temperature drop of the cooling water) is due to the latent heat of evaporation of a portion of the cooling water. The air flowing through the water spray also absorbs some sensible heat.

After dropping to the bottom of the tower, the cool water collects in a basin and is pumped back to the condenser. The amount of water lost as water vapour leaving the tower, the amount of **drift**, and the blowdown rate determine the amount of make-up water needed to maintain the tower basin level.

The rate of heat transfer in any cooling tower system depends on the:

- Relative velocity of both air and water during contact
- Area of water surface in contact with the air
- Length of contact time between the air and water
- Difference between the inlet water temperature and the inlet air wet bulb temperature (relative humidity of the air)

Purpose of Cooling Towers

Cooling towers transfer heat, in order to reduce the temperature of cooling water. Another way is to say that cooling towers reject heat from processes to a **heat sink** (the atmosphere). This heat rejection is accomplished by a sensible heat transfer (heating the air that passes through the tower), and the removal of latent heat caused by the evaporation of a certain percentage of the water. The heat required to evaporate this small portion of water is drawn from the remaining water, therefore cooling it.

The cooling tower rejects heat from equipment that generates heat (such as refrigeration and steam plant condensers), and cools water for reuse. In this way, a large proportion of the cooling water is recycled, reducing the plant's reliance on potable water sources or natural bodies of water. This is very important when large bodies of water, groundwater, or potable water are scarce or costly.

As well, other power plant equipment needs cool water to function properly. Bearings, lube oil coolers, internal combustion engine cooling systems, compressor cooling systems, and others rely on cool water supplied from cooling towers.

Cooling Tower Components

Refer to Figure 5. The basic components of a cooling tower are:

- Inlet water distributing box or sprays
- Packing, fill, or baffles
- Air moving equipment
- Inlet air louvres
- Drift eliminators
- Cooled water basin

In addition, cooling towers require a make-up water source, a water level control, chemical treatment equipment, an overflow, and (in some climates) a sump basin heater. These items are not shown in Figure 5.

Figure 5 – Cooling Tower

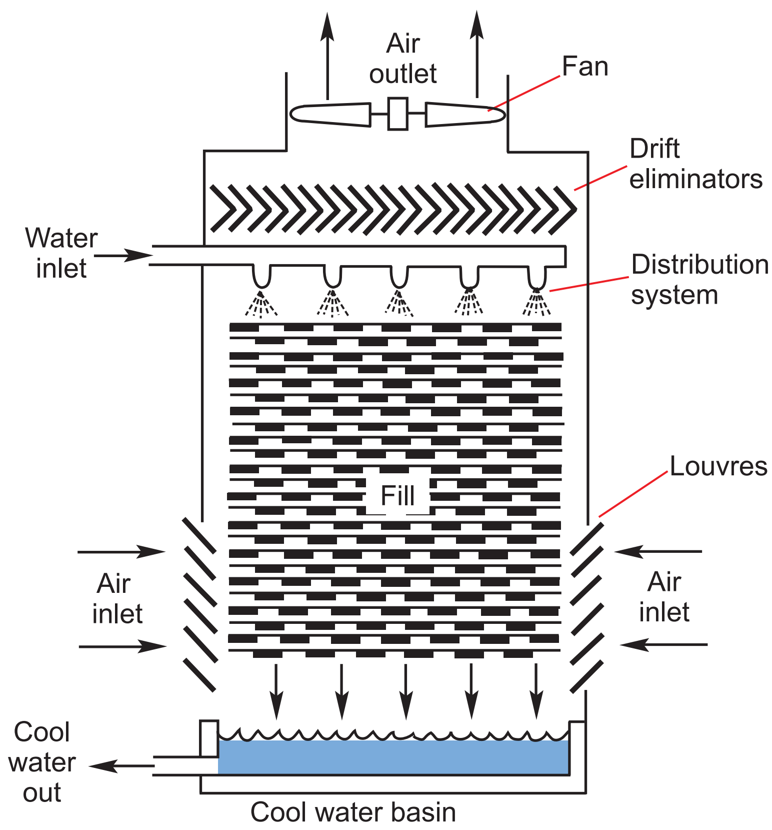


Figure 6 shows a cooling tower used to provide condenser water for large HVAC chillers in a hospital complex. Compare this image to Figure 5.

Figure 6 – Crossflow Cooling Tower in Service

Objective 3

Describe the construction and operation of natural draft cooling towers.

Cooling towers are divided into two classes according to the method of air circulation:

- Natural draft
- Mechanical draft

This objective discusses natural draft towers.

Natural Draft Cooling Towers

Natural draft cooling towers are subdivided into:

- Atmospheric towers
- Chimney towers (which are used mainly in large generating stations)

Atmospheric towers (Figures 7 and 8) are those in which the air movement through the tower is dependent on atmospheric conditions. The sides have louvres to direct airflow and reduce water loss by mist. These towers operate effectively only in locations where there are relatively constant winds and large open spaces.

Figure 7 – Atmospheric Spray-Filled Tower

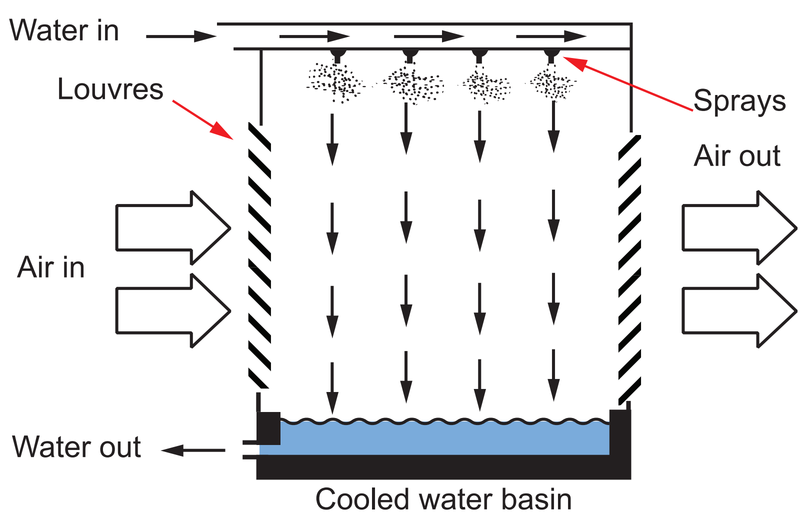
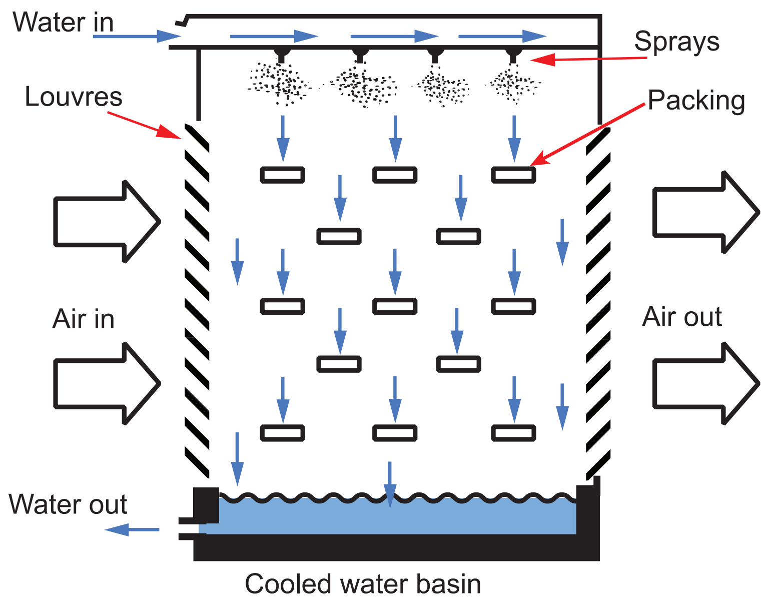


Figure 8 – Packed Atmospheric Tower



Chimney towers (Figure 9) are used mainly in large generating stations. They are also known as hyperbolic towers. This type is built with reinforced concrete in sizes up to 25 000 m³/h water circulation rate, with a base diameter up to 60 m, and a height reaching 90 m. The air inlet, water distribution, and fill are similar to a mechanical draft tower. But the majority of the tower height is purely chimney, to induce natural convection airflow.

Figure 9 – Natural Draft Chimney Tower

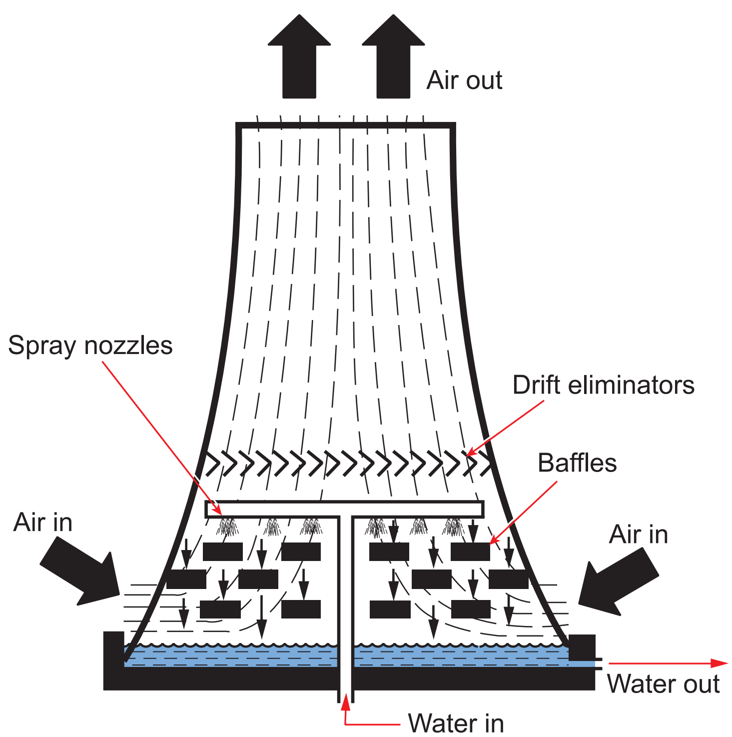


Figure 10 shows two of these large cooling towers in-use at a thermal generating station. Notice the water vapour exiting the top of the tower. This vapour is carrying sensible and latent heat.

Figure 10 – Natural Draft Chimney Tower

Water falls from a perforated overhead distribution flume, or from distribution spray nozzles, down through the packing (or decks). The water strikes the faces of the tower decking and breaks into fine particles. Air in contact with the hot water is warmed, and rises up the chimney. Cooler ambient air is drawn through the louvres, and into the base of the tower. During this process, the fine particles of water come in close contact with the air currents, which enhances the process of evaporation and cooling.

Cooling Tower Operating Checks and Maintenance

To ensure continuous effective operation of the tower, a regular inspection and maintenance schedule should be implemented. It should include:

a) Cleaning the louvres, piping, and nozzles to ensure that they are free of scale, algae, and dirt.

b) Cleaning the water basin and checking for leaks.

c) Cleaning the suction screen.

d) Checking that the level control valve is operating properly.

Possible operational problems and their causes are:

a) High discharge water temperature from the tower. Probable causes of this can include:
   i. High ambient air temperature
   ii. High concentration of solids in the water
   iii. Restriction of air flow through the tower
   iv. Poor water breakup due to worn or dirty nozzles and diffusers
b) A reduction in water flow which may be due to restrictions created by algae, scale, or dirt.
c) Tower basin or sump overflowing. A clogged sump screen, a restriction in the water outlet piping, or an improper level control valve operation may cause this overflow.
d) Excessive wind velocity, broken or missing louvres, or excessive water pressure in the nozzles may cause excessive water drift.

Objective 4

Describe the construction and operation of mechanical draft cooling towers.

Mechanical Draft Cooling Towers

Mechanical draft towers use one or more fans to move large quantities of air through the tower. They are divided into two subclasses:

- Forced draft cooling towers
- Induced draft cooling towers

The airflow in either class may be **crossflow** or **counter-flow** with respect to the falling water. Crossflow indicates that the airflow is perpendicular to the flow of falling water. Counter-flow means the airflow is in the opposite direction of the falling water.

The counter-flow tower occupies less floor space, but is taller to accommodate a given capacity. The main advantage of the crossflow tower is the low-pressure drop (because it requires less height) in relation to its capacity. It also has a lower fan power requirement, which leads to lower energy costs.

All mechanical towers must be located so that the discharge air diffuses freely without recirculating through the tower, and the air intakes are not restricted. Cooling towers should be located as near as possible to the systems they serve. However, they should not be located below them as this positioning could allow the condenser water to drain out of the system, and back through the tower basin when the system is shut down.

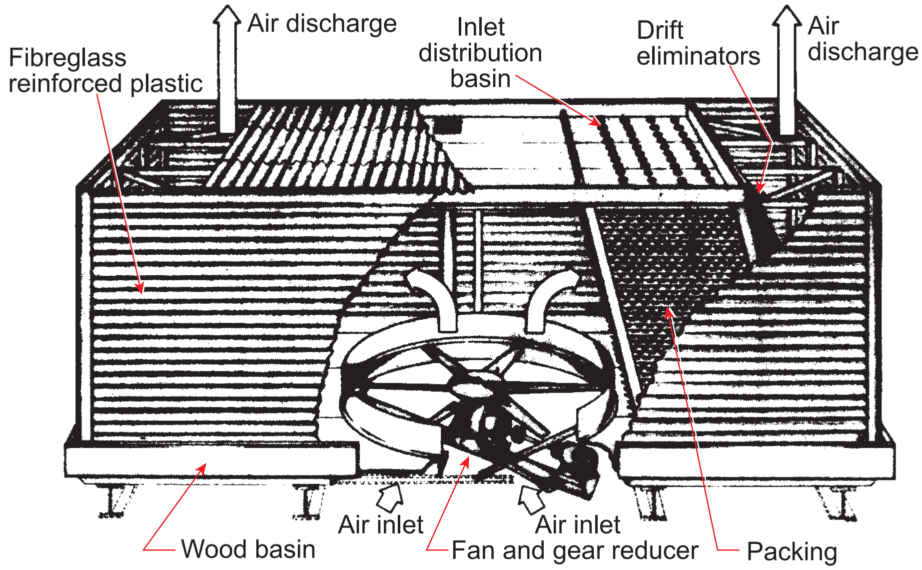
Forced Draft Cooling Towers

The forced draft tower, shown in Figure 11(a), has the fan, basin, and piping located within the tower structure. In this model, the fan is located at the base. There are no louvred exterior walls. Instead, the structural steel or wood framing is covered with paneling made of aluminum, galvanized steel, plastic, or fiberglass panels.

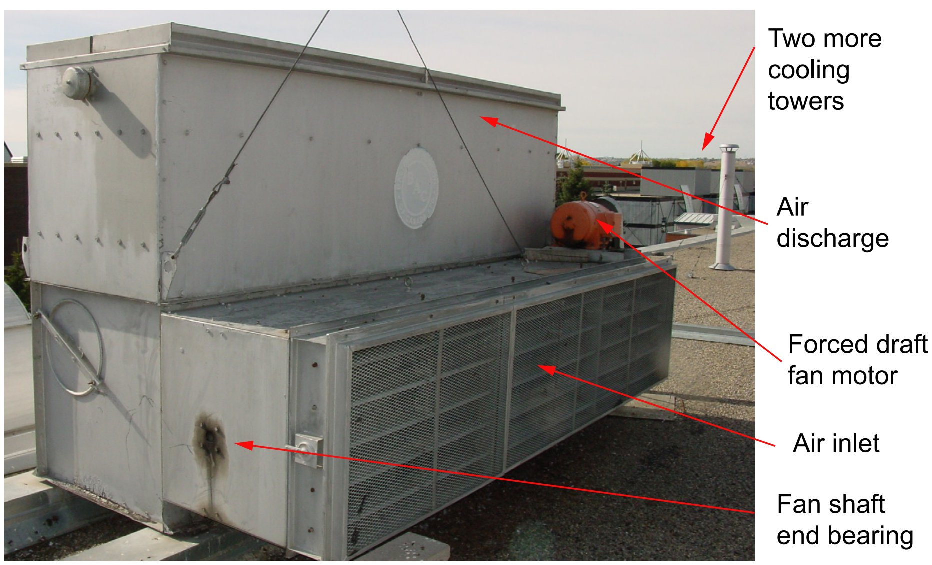
During operation, the fan forces air, at low velocity, horizontally through the water that falls vertically over the packing. The warmer air, at higher humidity, flows vertically out the top of the tower. The **drift eliminators**, located where the air exits the packed section, remove water entrained in the air. Vibration and noise are minimal since the rotating equipment is built on a solid foundation. The fans handle mostly dry air, which reduces corrosion problems.

Figure 11(b) is a similar cooling tower with an electric motor turning four squirrel cage fans on a common shaft. The end bearing of the shaft is labelled. The warm water enters the tower at the back, and drops downward into a basin. Then it drains, by gravity, back to a cooling water storage tank. Drift eliminators are located in the air discharge plenum. There are two crossflow cooling towers off in the distance at the right of the picture.

Figure 11 – Forced Draft Tower



(a)

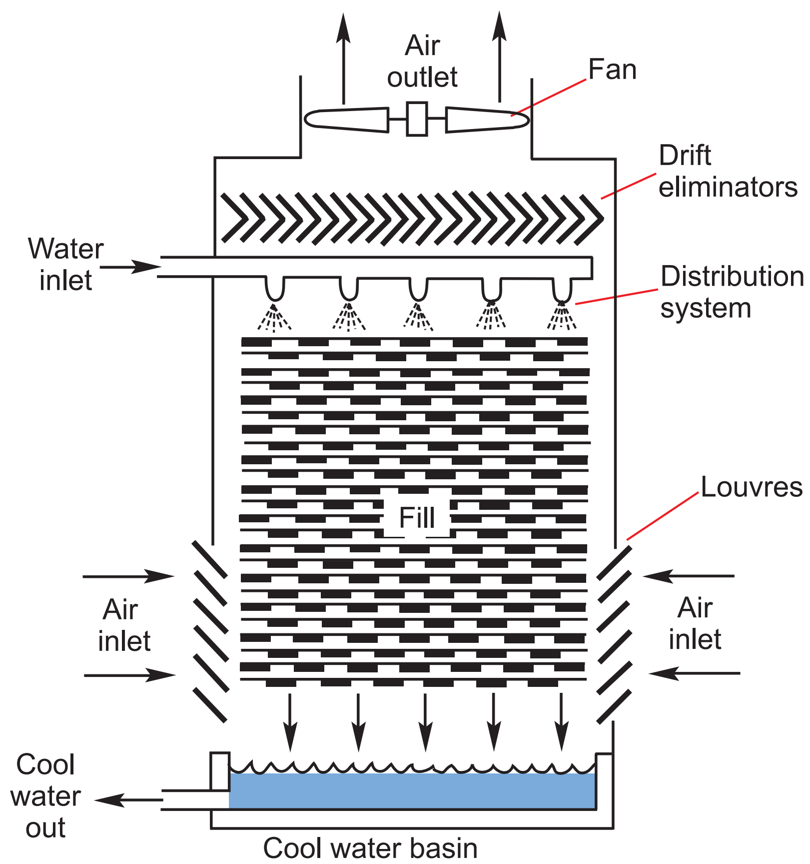


(b)

Induced Draft Cooling Towers

The induced draft tower (Figure 12) has one or more fans, located at the top of the tower. The fans draw air upward against the downward flow of water passing around the wooden decking or packing. Since the airflow is counter to the water flow, the coolest water at the bottom is in contact with the driest air, while the warmest water at the top is in contact with the moist air. This increases heat transfer efficiency.

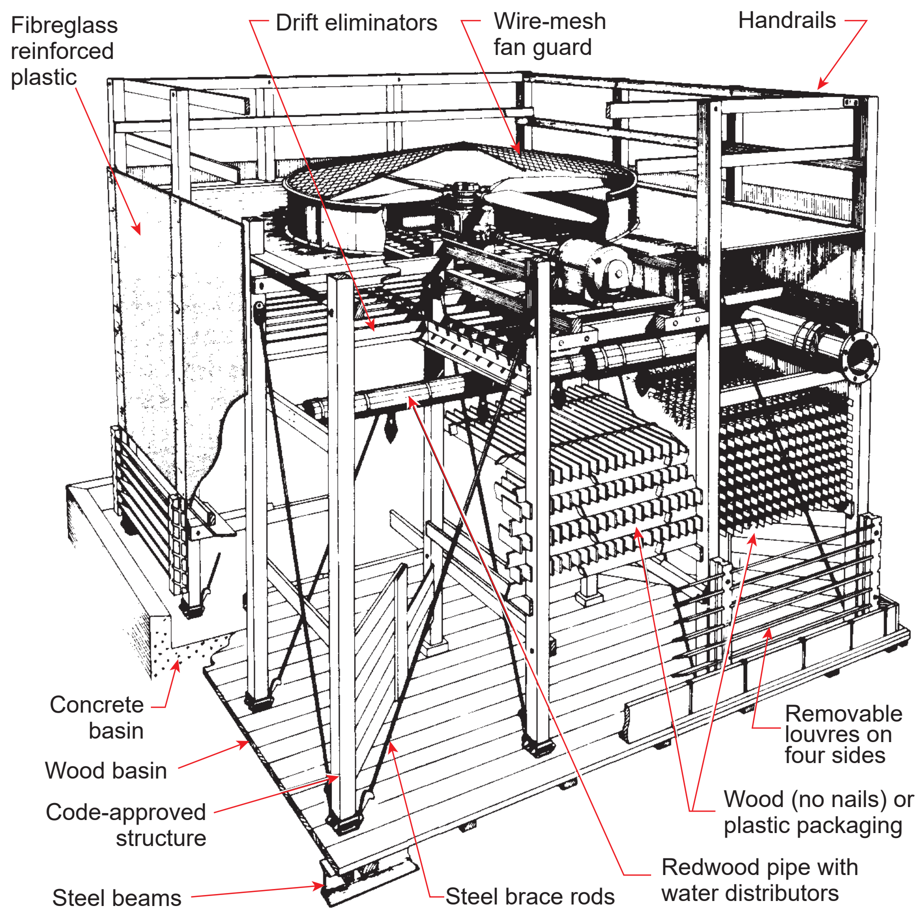
Figure 12 – Counter-Flow Induced Draft Cooling Tower



The fans at the top discharge the hot, moisture-laden air upward and away from the air entering at the bottom of the tower. This prevents any recirculation of warm air. Warm water from the building enters the distribution system, which is located just under the drift eliminators. The fans and their drives are mounted on the top deck.

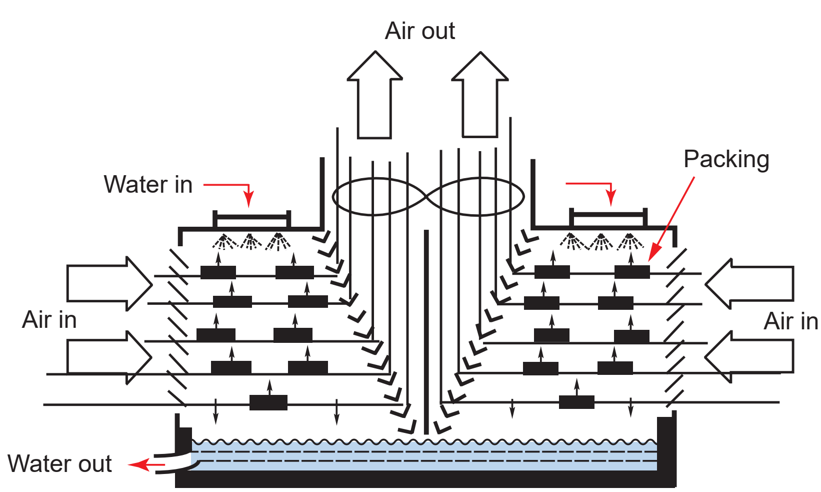
Figure 13 illustrates the components of a counter-flow induced draft tower in more detail. This type requires large electric motors because of the cumbersome path that the air has to take.

Figure 13 – Counter-flow Induced Draft Tower



Another type of induced draft tower, called the crossflow, is shown in Figure 14. Crossflow towers provide horizontal airflow as the water falls through the packing. Single and double air inlet designs are constructed to suit the job location and operating conditions.

Figure 14 – Crossflow Tower Design



The fans, located at the top, draw air through cells (or packing) that are connected to a suction chamber partitioned midway beneath each fan. The water falls from the distribution system in a cascade of small drops over the packing and across the horizontal flow of air. The total travel path of the air is longer, and there is less resistance to airflow than in the counter-flow design.

Dry Cooling Towers

The dry tower is another type of cooling tower used for situations where the cooling water supply is unavailable or highly restricted. The cooling water passes through finned tubes placed in the tower in banks. Air currents, produced by mechanical or natural means, cool the water. Using this closed-circuit method eliminates contact between the water to be cooled and the coolant air. This eliminates water loss by evaporation and drift, and there is no make-up water required. A small-scale example of this type of cooling is an automobile radiator.

Mechanical Draft Cooling Tower Maintenance

The following are general maintenance guidelines for mechanical draft cooling towers:

1. Lubricate the fan motor every three months, or as specified by the manufacturer, using the recommended lubricant.
2. On V-belt driven fans, lubricate the fan shaft monthly, and check the tension on the belt.
3. Check all tower bolts monthly.
4. Check the float valve monthly.
5. Clean and repaint corroding exterior metal surfaces annually. Inspect the interior of the tower at this time.
6. Clean fan blades annually. Inspect them for cracks, and paint if necessary.
7. Clean and balance fans when high vibration levels are detected.
8. Consult a water treatment specialist if scaling or algae formation is evident.

CAUTION

All evaporative type cooling towers must be regularly cleaned and chemically treated to inhibit the growth of deadly bacteria, including Legionella Pneumophila (the cause of Legionnaires Disease). Proper personal protective equipment must be used while cleaning cooling towers.

Objective 5

Discuss cold climate operation for cooling towers.

Cold Climate Considerations

Cooling towers do not generally need protection from freezing while in operation. An acceptable thin layer of ice may form on the louvres, or air intake structure, of the tower. However, action must be taken if heavy ice forms on the inside, as this will jeopardize the heat transfer. Heavy ice may overload the cooling tower structure, causing supporting members to break.

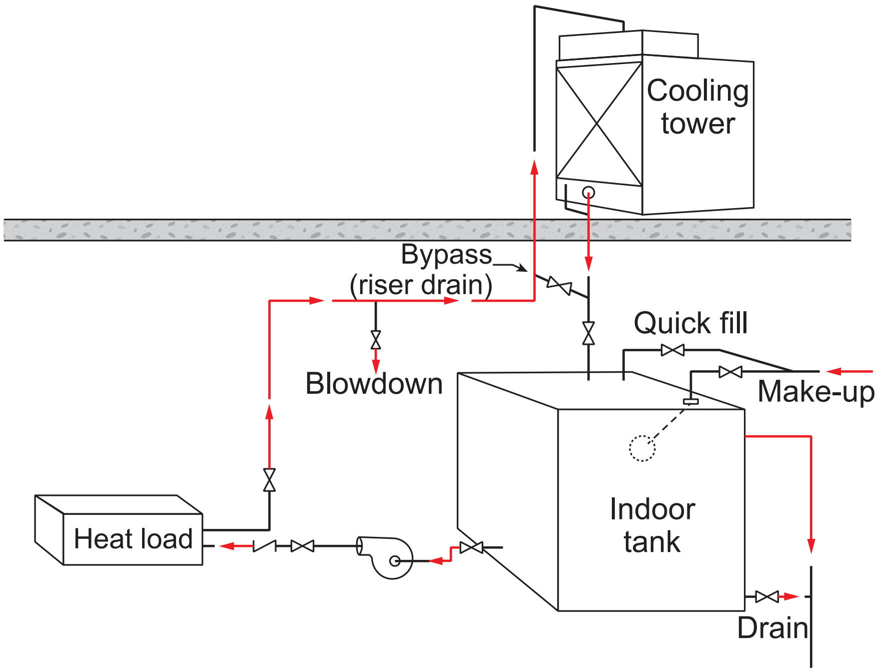
Control of both the water flow and the airflow can be useful. A bypass line is used to direct water flow to the water basin beneath the tower, instead of directing it over the fill. Total bypass is used during startup in cold weather. A partial bypass may continue during normal operations, in especially cold weather. When the water in the basin reaches about 27°C, depending on the tower manufacturer, the bypass should close so that all the water flows over the fill.

Airflow control, with the use of two-speed or variable speed fan motors, can reduce the amount of cold air that passes through the tower. This reduces heat loss from the cooling water. Severe ice formation on louvres may require that the fans be reversed for a period of time. This changes the pattern of falling water, and brings a deluge of warm water in contact with the ice, so it can rapidly melt.

When the tower is shut down, the water basin must not freeze. If possible, maintain some heat load and circulation of the cooling water. When this is not possible, other methods need to be employed.

- A remote sump pump for circulation is an alternative to low load operation.
- Thermostatically controlled electric heaters or steam coils are sometimes used to prevent the basin water from freezing.
- The indoor tank or dry basin method allows water to drain continuously from the tower basin to an indoor storage tank from where it is pumped to the condensers. A bypass line is used to drain the supply line, and regulate the cooling water temperature during cold weather and low loads, as in Figure 15. During a shutdown situation, the bypass line and the main basin drain allow water to flow into the indoor tank. This removes all water from the freezing environment above the roof level.

Figure 15 – Indoor Storage Tank for Winter Freeze Protection



Wood Deterioration

Many cooling towers are constructed of wood. This makes them susceptible to biological and chemical attack, which causes severe wood deterioration.

Wood is composed of cellulose, lignin, and natural extractives. Cellulose exists as long fibres, which give wood its strength. Lignin cements the cellulose fibres together. Extractives contain the natural compounds that enable wood to resist decay. Unfortunately, the extractives are water-soluble and they leach away, which leaves the wood in cooling towers vulnerable to decay.

Chemical attack occurs mainly as delignification. Its main agents are oxidizing agents, such as chlorine and alkaline solutions. Delignification can be controlled with the use of non-oxidizing biocides, or by keeping the chemical concentration of oxidizing agents sufficiently low.

Biological attack on cooling tower wood affects the cellulose. This is a source of carbon for the growth and development of microorganisms. Methods of control include:

- Use woods, such as redwood, that have a natural resistance to biological attack.
- Treat the wood with preservatives such as creosote or chromated copper arsenate, among others.
- Use a limited amount of nails, screws, or iron hardware. These accelerate deterioration to the wood in their vicinity.
- Treat the water with biocides.

Objective 6

Explain typical problems and resolutions required within the operation of cooling towers.

Cooling Tower Troubleshooting

Many problems can occur when a cooling tower is in operation. Below are common ones, with suggested remedies.

Excessive Water Drift

With regard to cooling towers, drift refers to when water particles become entrained with the flow of air leaving the cooling tower. Drift results in the following conditions:

- Increased make-up water requirements
- Increased water treatment requirements
- Reduction of tower cooling capacity. When moisture leaves the tower, it carries away only sensible heat. If the same mass of water remained with the greater body of cooling water, and then evaporated, it would provide significantly more cooling.

For these reasons, drift should be eliminated or reduced to a minimum.

Several factors can cause excessive water drift. These include:

- Missing louvres that allow air to sweep rapidly through the tower, and lift out the spray of water.
- Incorrectly placed or plugged splash bars or fill that causes water to pool, which the air stream will lift out.
- Drift eliminators that are missing or out of place, that allow the air stream to carry out excessive amounts of water.
- Over pumping. This can cause excessive water drift by overloading the tower's fill and splash bar system. Reduce the water flow to the spray headers, or to the upper basin, with the volume control valves.

Outlet Water Temperature High

The outlet water temperature may rise for a number of reasons.

a) Water is supplied at too high a rate for it to splash and break up. The evaporative effective will not work, and the water will not cool.

b) Splash bars or fill are not in place to break up the water. High temperatures will result.

c) Spray nozzles that help to break up the water are worn. This will allow the water to stream out instead of spray, which causes poor cooling effects.

d) Fill has a growth of algae or slime on the surface. This will not allow the water to evenly flow and splash on and around the fill.

e) Airflow into the tower is blocked or impeded.

Fan Motor Fails to Start

If a fan motor fails to start, there may be a control issue, or a motor issue. The fan motor will only run when necessary, to maintain a cooling water set point temperature. Controls that are set incorrectly will keep the fan motor from starting. Confirm the start and stop temperature settings for the fan motor.

Usually, there is a vibration switch on the tower to shut off the fan motor, should the vibration from a bad or imbalanced fan blade occur. Before resetting the vibration switch:

1. Lock out the fan motor. Follow plant procedures.
2. Check the fan blades for tightness to the hub, excessive deposits, large nicks or other fan blade damage, missing blades, or mission portions of blades.
3. Reset the vibration switch if everything appears normal.
4. Unlock the fan motor, and monitor the fan operation from a distance.

If the fan motor does not start, review the problem and solutions for electric motors and starters.

Motor Problems

Motor Noise

If the motor is making unusual noises, check for vibration of the motor at both ends. If the motor is vibrating and is hotter than usual, there may be a bearing problem.

Motor Overheating

If a tower fan motor overheats, it could be due to the following:

a) Ventilation holes may be covered with dirt, vegetation, dust, or feathers. Clear off the openings, and keep clean at all times.

b) Changes in fan blade pitch can overload the motor. Safely stop the motor, and lock it out. Check the blade pitch to see if any blades have moved, or if the pitch is no longer at the required angle. If any blade tips are hitting the shroud around the fan, this could be an indication of the fan blade pitch changing, or a fan blade getting stressed. Spin the fan blade while it is locked-out, and see if there is excessive drag from the gearbox or belt system.

Gear Reducer Concerns

The gear reducer system may cause problems if improperly maintained. Inside the reducer are gears, shafts, and bearings. There should also be sufficient oil to lubricate the equipment. Check the oil level on every round. The oil could leak out, and cause the gearbox to seize, which will contaminate the water in the cooling tower. Gaskets and bolts will loosen or deteriorate over time. If the gearbox is hot and making grinding growling noises, shut it down and prepare to overhaul the gearbox.

The gearbox may be coupled to the fan drive through a drive shaft or belts. A belt drive system needs to have the belts replaced frequently, due to exposure to the weather and running conditions. A drive shaft does not need as much maintenance, but could cause problems at the couplings, or at the flexible universal joints. These joints and couplings need to be lubricated at suggested intervals, or they will cause vibration, and possibly stop the operation of the tower.

Insufficient Water Flow

A plugged strainer, before the pump, will impede water flow. Cooling water picks up dirt, dust, debris, leaves, flowers, fluff, and other airborne matter. This gets trapped in the suction strainer of the pump, and starves the pump of water. If water treatment has not been maintained, scale and sediment in the pipes may break off. These can lodge in the distributor lines, nozzles or spray heads, and cause a loss of water flow.

Tower Construction Materials

The tower construction materials (wood, plastics, or metal) will eventually wear, corrode, or be damaged by the sun's rays. Keep up a good water treatment program to reduce the attack on the wood and steel components. Inspect louvres, baffles, and fill to ensure that they are not deteriorating quickly, and replace pieces as necessary.

Chapter Summary

This chapter covered the application and operation of condensers and cooling towers in industry. Condensers and cooling towers are common to many power plants. These heat exchangers reject heat from plant processes and equipment.

Contact condensers were once common; however, they contaminate condensate with cooling water. Surface condensers now dominate industry, because they can provide condensate with high purity.

Cooling towers are used to conserve scarce water resources. They may be atmospheric, natural draft, or mechanical draft. Atmospheric cooling towers have the benefit of mechanical simplicity. Mechanical draft cooling towers have more capacity, though. Chimney-type hyperbolic cooling towers are most common in very large industrial and in power generation facilities.

Cooling towers must be properly maintained, so they do not rot or corrode. Bacterial growth must be prevented, so that harmful and deadly bacteria do not develop in the cooling water. They must also be protected from damaging cold temperatures A variety of methods were discussed.

Cooling towers, like other power plant equipment, require regular maintenance to ensure they operate correctly. Problems with cooling towers can be recognized early, by monitoring the temperature of the cooling water. Increasing temperature indicates problems with fans, motors, biological growth, or structural failures. These were discussed in the last objective.

CHAPTER 4

Gas Turbines

LEARNING OUTCOME

When you complete this chapter you should be able to:

Describe the application, startup, operation, and maintenance required for gas turbines.

LEARNING OBJECTIVES

Here is what you should be able to do when you complete each objective:

1. *Describe the principle of construction and operation of gas turbines.*
2. *Identify the operational characteristics of gas turbines.*
3. *Describe regeneration and combined steam-gas turbine operating cycles.*
4. *Describe the key elements of gas turbine startup, operation, and auxiliaries.*

Chapter Introduction

A gas turbine is both a heat engine and a prime mover. When the fuel burns, it adds heat to the compressed air. The heated air then expands through the blades of the turbine. Gas turbines use the same principles as steam turbines to produce power. They both harness the work done by expanding gases, and therefore use similar blading. The gas turbine principle has been around for many years. But, for technical reasons, there was a delay in applying it in industry. Early gas turbines were handicapped by a lack of metals that could withstand high temperatures. Furthermore, air compressor and turbine efficiencies were not high enough to give a profitable net power output. These low efficiencies meant that essentially all of the turbine output was applied to run the compressor.

Today, the gas turbine is supreme in the field of aircraft propulsion. It finds use for stationary power generation for small standby or emergency equipment, and large capacity electrical generating stations. To a limited extent, it has been used for marine propulsion; and experimental units have been built and operated in automobiles.

Objective 1

Describe the principle of construction and operation of gas turbines.

Gas Turbine Principle

The simple gas turbine has an upstream compressor attached to a downstream turbine, with a combustion chamber between them. This prime mover operates by drawing air into a compressor and then discharging compressed air into the combustion chamber. There, fuel is added and burned, which further heats the air. The hot air then expands through the turbine to provide power. About two-thirds of this power is used to drive the compressor. The remaining power is available to drive a load or provide thrust.

The efficiency of a gas turbine depends primarily upon the temperature to which the air can be raised before it enters the turbine. The higher the combustion temperature, the more efficient the machine. Hence, it is best to operate gas turbines at the maximum possible temperature that its construction materials can handle.

The output power (power rating) of the machine depends upon the mass of hot gas flowing through it per unit time. Thus, the output of a gas turbine increases when operating with inlet air of high density. For this reason, cold air at the compressor intake produces a marked increase in gas turbine output.

The following sections on aircraft gas turbines will help to illustrate the operating principle of all gas turbines.

Types of Industrial Gas Turbines

There are two basic types of industrial gas turbines:

Aeroderivative gas turbines, which are derived from the jet engines used in aircrafts.

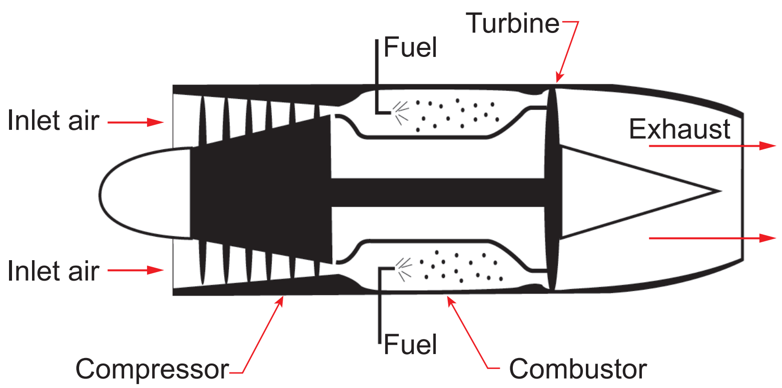
Heavy-duty gas turbine, which are designed only for land-based applications.

Each type has advantages and disadvantages to make them suitable for specific applications. However, there is considerable overlap in their abilities, so there are no hard and fast application rules.

Aeroderivative Gas Turbine

Figure 1 shows a schematic diagram of a basic gas turbine. Air is drawn in and compressed by a rotating axial compressor, then passed into a combustion chamber (or combustor), where fuel is injected and burned. The hot compressed gas (mostly air) is then allowed to expand through the blades of a turbine.

Figure 1 – Basic Single-Shaft Gas Turbine

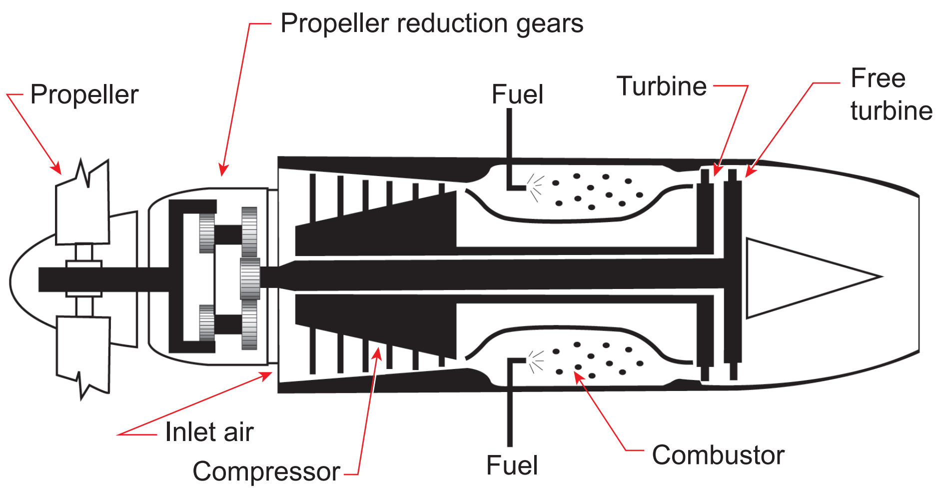


The turbine and compressor are on the same shaft. The turbine drives the compressor with this shared shaft.

The gas turbine shown in Figure 1 is an aircraft turbojet engine. The aircraft thrust is obtained from the reaction effect of the flow of exhaust gases.

Figure 2 shows the application of a propeller drive to a gas turbine. The basic gas turbine is the same. Air is drawn in, compressed, heated, and finally expanded through turbine blading.

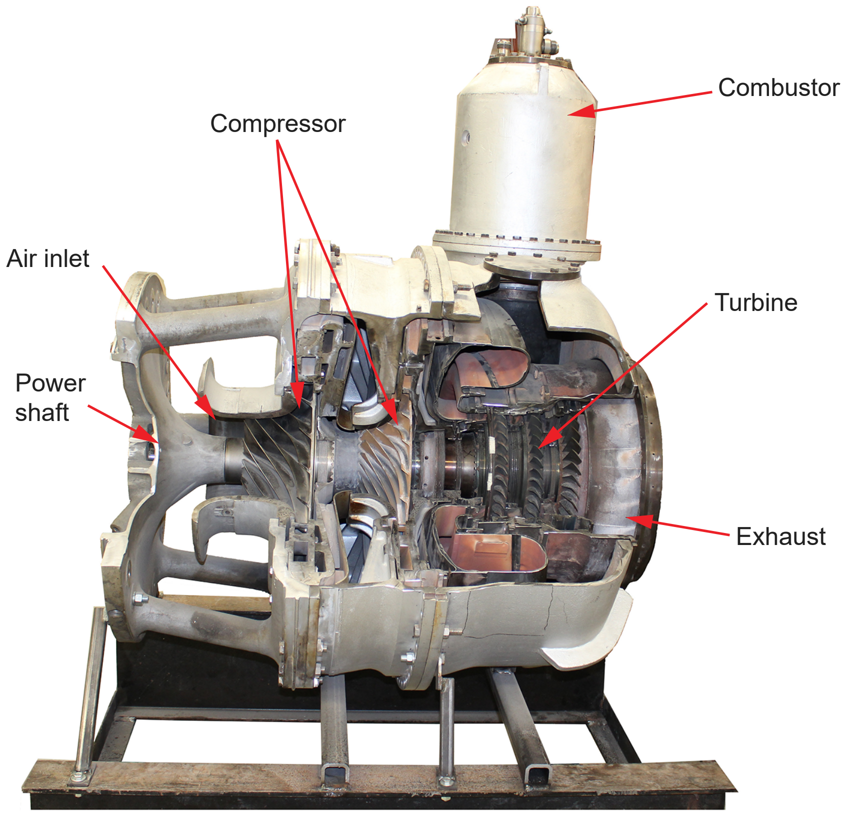
Figure 2 – Basic Two-Shaft Gas Turbine



However, in this case, there are actually two turbines. One is on the same shaft as the compressor. The output of this turbine is entirely absorbed by driving the compressor. The other turbine is free of the compressor. This second turbine drives the propeller, utilizing reduction gears. This machine is the typical turboprop aircraft engine.

Figure 3 is a sectional view of a small gas turbine, and shows the major engine parts.

Figure 3 – Small Gas Turbine



The gas turbine shown in Figure 3 has a two-stage centrifugal compressor. The turbine in Figure 4 has an axial compressor, comprised of alternating rows of rotating stationary blades. It is referred to as an axial compressor because the air travels parallel to the compressor shaft.

Figure 4 – Section Through 450 kW Gas Turbine

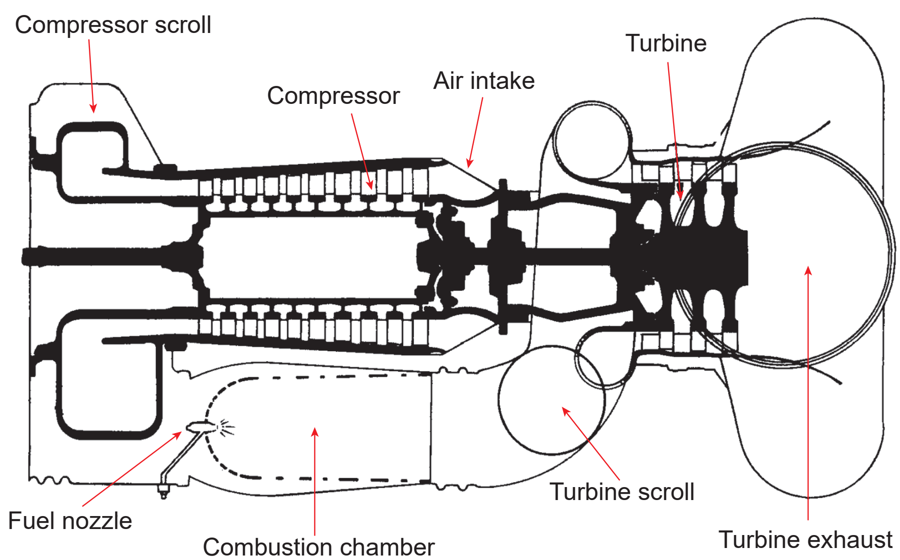
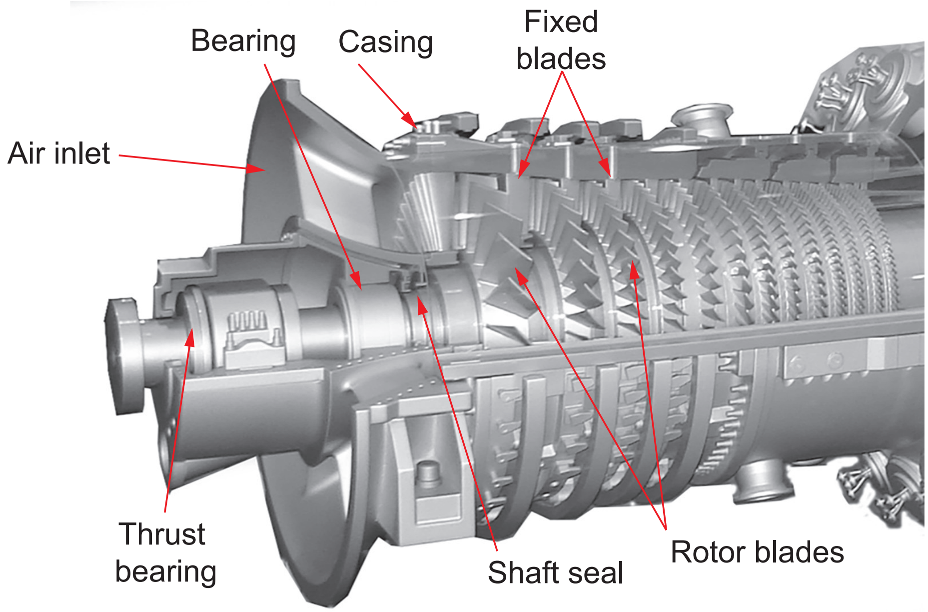


Figure 5 shows a more detailed view of the air compressor impeller. Note the reduction in the size of the blading as the air passes through this axial compressor.

Figure 5 – Compressor Impeller

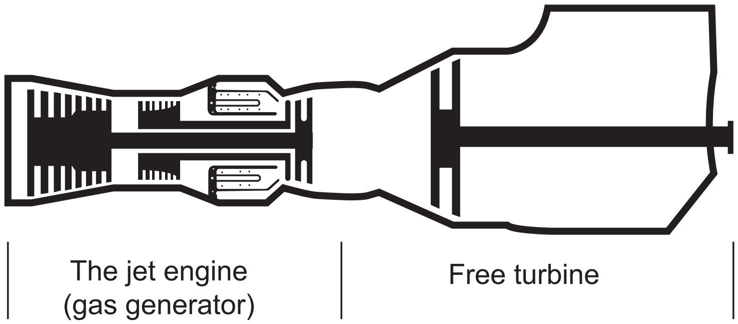


Heavy-Duty Gas Turbine

The aeroderivative gas turbine demonstrated that it could be applied to industrial needs. However, small gas turbines are often used to produce power for portable and standby generators, fire pumps, and compressors. Larger, specially modified units are used to generate electricity in stationary plants.

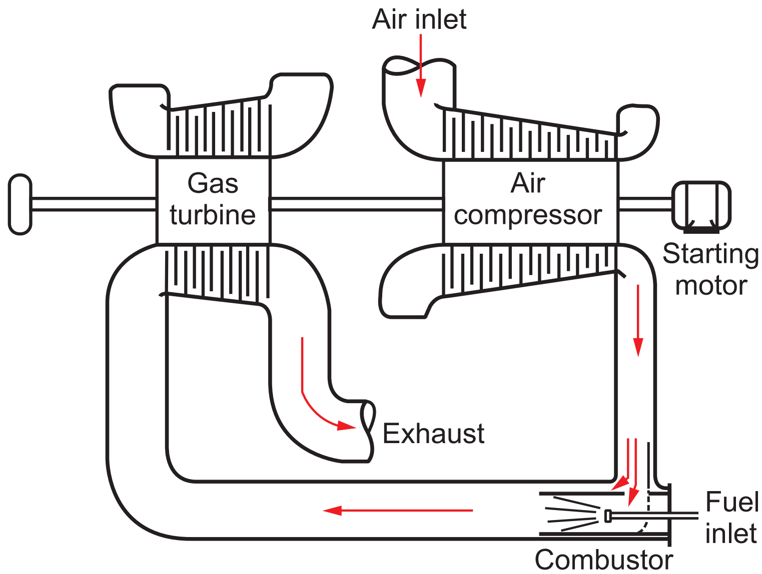
Figure 6 is a diagram of an aircraft gas turbine with a free turbine connected to a mechanical load. The exhaust is directed up the plant stack.

Figure 6 – Aeroderivative Gas Turbine Supplying a Free Turbine



As the demand for higher output gas turbines increased, designs became more specialized to meet the needs of stationary plants. The combustion chamber was separated from the engine body. The air and hot gas were ducted from the compressor to the turbine in the manner shown in Figure 7.

Figure 7 – Single Turbine Unit Without Heat Exchanger



The gas turbine and air compressor have multiple rows of blades. This design makes it possible to deliver a considerable amount of useful power.

Note that rows of stationary blades alternate with rows of rotating blades. Each stationary blade redirects the hot gases or air against the passing rotating blades.

A gas turbine is not self-starting. Therefore, it must be rotated at 20 to 30% of its maximum speed before fuel is turned on. This rotation is done to give sufficient air compression so that, when fuel is injected, the gas turbine power will be able to drive the compressor and maintain the speed rise. Consequently, a starting motor is an essential auxiliary.

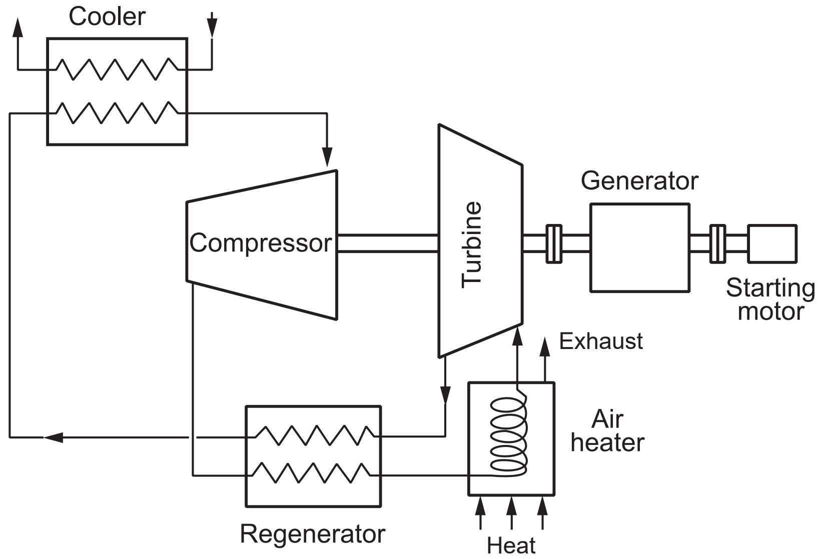
The gas turbine illustrated in Figure 7 is called a simple, open-cycle, single shaft gas turbine. These terms are defined as follows:

Simple gas turbine: it has no heat exchanger, regenerators, or intercoolers.

Open-cycle gas turbine: it draws the air used to drive the turbine from the atmosphere, and returns the air to the atmosphere after use. Alternatively, a closed-cycle (shown in Figure 8) recycles the working fluid back to the compressor inlet.

Single shaft gas turbine: it has only one shaft. The gas turbine and the compressor are mechanically coupled together on the same shaft.

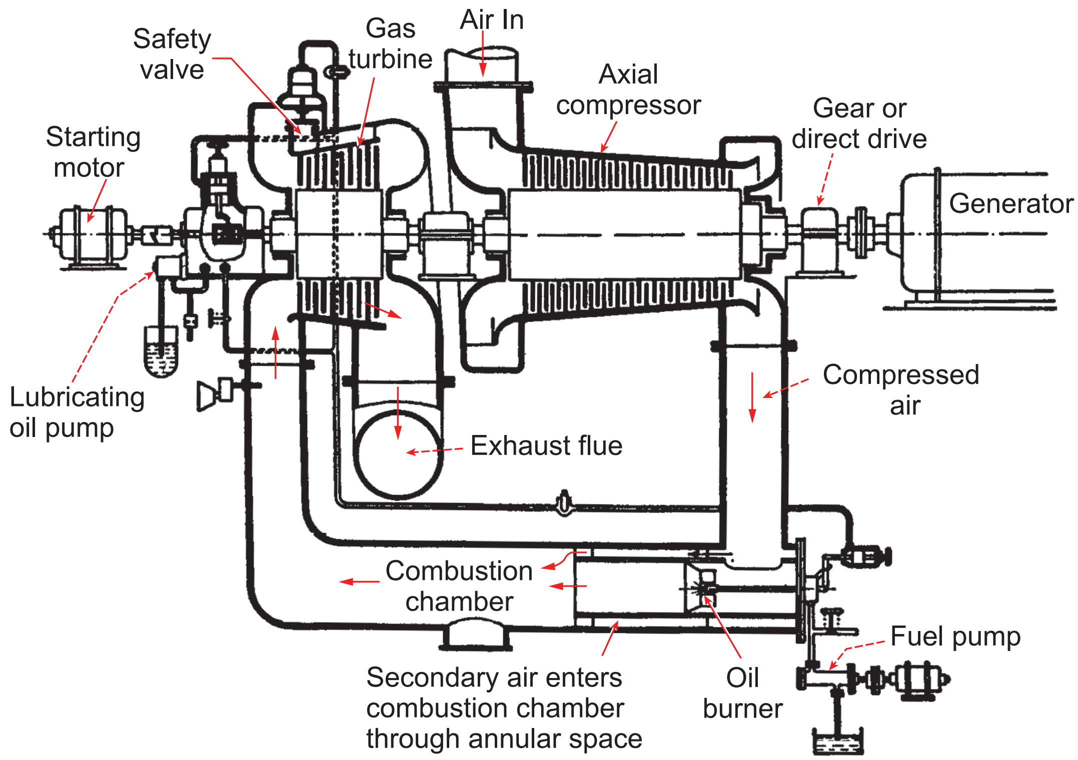
Figure 8 – Closed-Cycle Gas Turbine



The majority of gas turbines in industrial use are simple, open-cycle, single shaft machines.

Figure 9 shows a gas turbine unit of this type, designed for use in a thermal electric generating facility. This peak-load power station includes a high-efficiency air compressor, a combustion chamber, and a multi-stage reaction turbine.

Figure 9 – Continuous Combustion Gas Turbine



(Courtesy of Allis-Chalmers)

Figure 10 is a sectional view of a simple, open-cycle, two-shaft gas turbine. The turbine power is rated at 1045 kW when running at 6000 r/min.

Figure 10 – Simple, Open-Cycle, Two-Shaft Gas Turbine

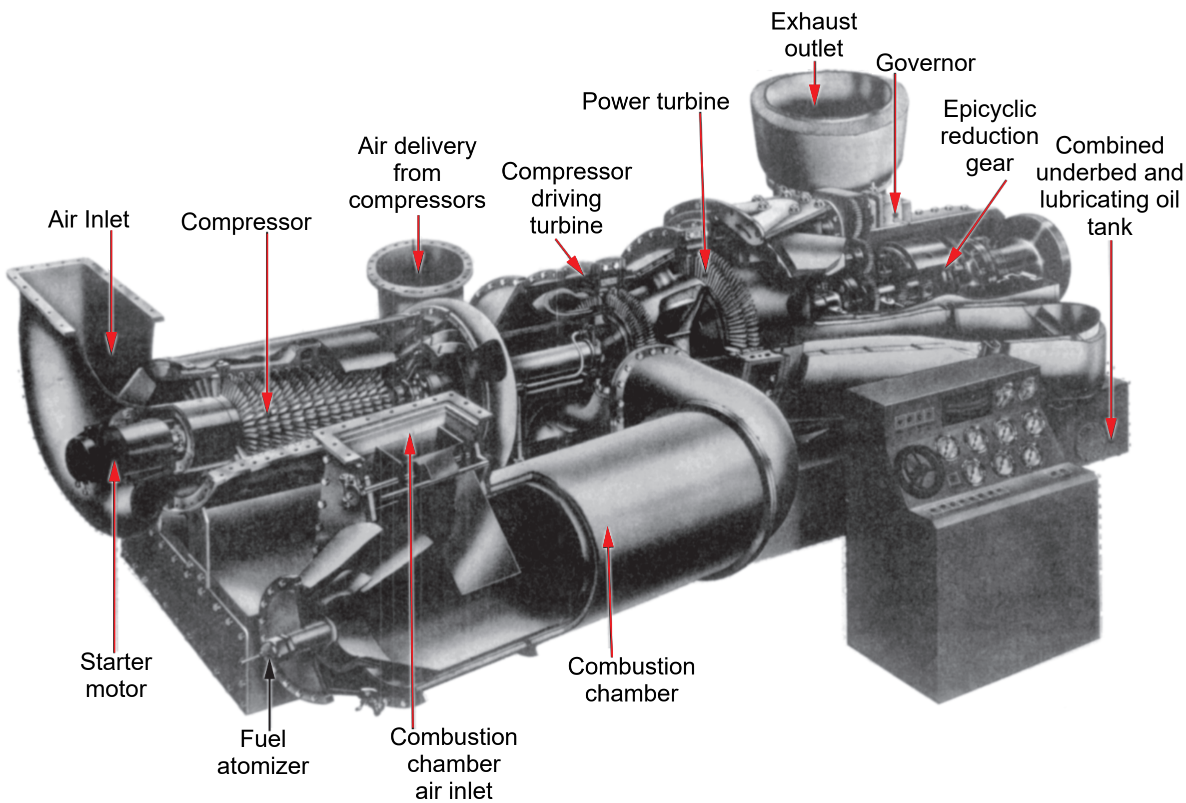
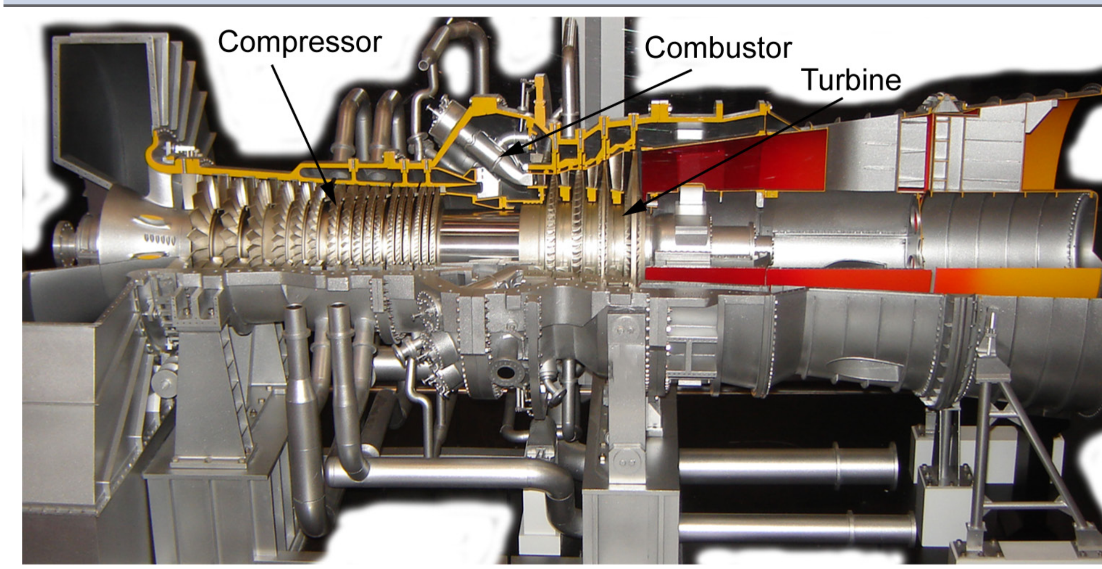


Figure 11 is a cutaway picture of a modern 300 MW gas turbine.

Figure 11 – Gas Turbine Main Parts



Objective 2

Identify the operational characteristics of gas turbines.

Gas Turbine Characteristics

Gas turbines have certain characteristics which distinguish them from other types of prime movers. Some of these traits have proven to be advantageous, and some of them are disadvantageous.

Advantages

Some advantages of gas turbines include:

- High power to weight ratio
- Low installed cost
- Low maintenance and operating cost
- Minimum cooling water
- Rapid startup and loading

High Power to Weight Ratio

Compared to a steam plant, a gas turbine of the same output is much smaller and lighter. Gas turbine plants are also less mechanically complex. These are considerable advantages since the building that houses a gas turbine plant can be smaller, and needs only a light foundation.

Low Installed Cost

The capital cost of a gas turbine plant is lower per watt of output than a steam plant. The gas turbine cost includes the functions that, in a steam plant, would be performed by the boiler, steam turbine generator, condenser, boiler feed pump, and feedwater heaters.

Low Maintenance and Operating Cost

The absence of reciprocating motion minimizes wear on the moving parts. Lubricating oil consumption is low. Because of the simplicity of a gas turbine, it eliminates many auxiliaries required in a steam plant. The result is lower operating costs in stations that have a comparable rating.

Minimum Cooling Water

Gas turbines require a minimum of cooling water. They can operate economically with a closed circulating water system by using air-cooled heat exchangers. This makes gas turbines ideal for use wherever water is scarce or unobtainable.

Rapid Startup and Loading

A gas turbine can be started almost instantaneously. It does not require slow and elaborate preparations, as does a steam turbine used in conjunction with a steam generator. Further, since the blade clearances in a gas turbine are greater than those of a steam turbine, it can be loaded up to full load much more rapidly. These considerations make the gas turbine ideal for standby duties, such as fire pumps and emergency electricity generators, where instant starting is essential, or where remote operation by telemetry is required. They are also well adapted to supply the mechanical drive for electrical generators operated only to supply peak electrical loads.

Disadvantages

Some disadvantages of gas turbines include:

- Low mechanical/thermal efficiency
- High noise level
- Limited types of fuel
- NO_X emissions

Low Mechanical/Thermal Efficiency

Traditionally, simple, open-cycle gas turbines have lower thermal efficiency than steam plants, diesel engines, or gasoline engines. To improve thermal efficiency, auxiliary equipment (such as regenerators) were added in order to make the gas turbine competitive. However, regenerators cost more and add maintenance to gas turbine installations.

Other technological advances have also increased gas turbine thermal efficiency:

- More efficient compressor blades
- Increased compression ratio
- Better materials, capable of withstanding higher combustor and turbine temperatures.

It should be noted that, in some applications, reliability is essential. Economy of operation is a secondary concern.

Gas turbines have a low mechanical efficiency since 2/3 of the power output is required to run the air compressor. The output and efficiency is also effected by ambient air pressure and temperature, more so than a conventional plant.

High Noise Level

Unless special precautions are taken to baffle the exhaust, the gas turbine is a noisy machine.

Limited Types of Fuel

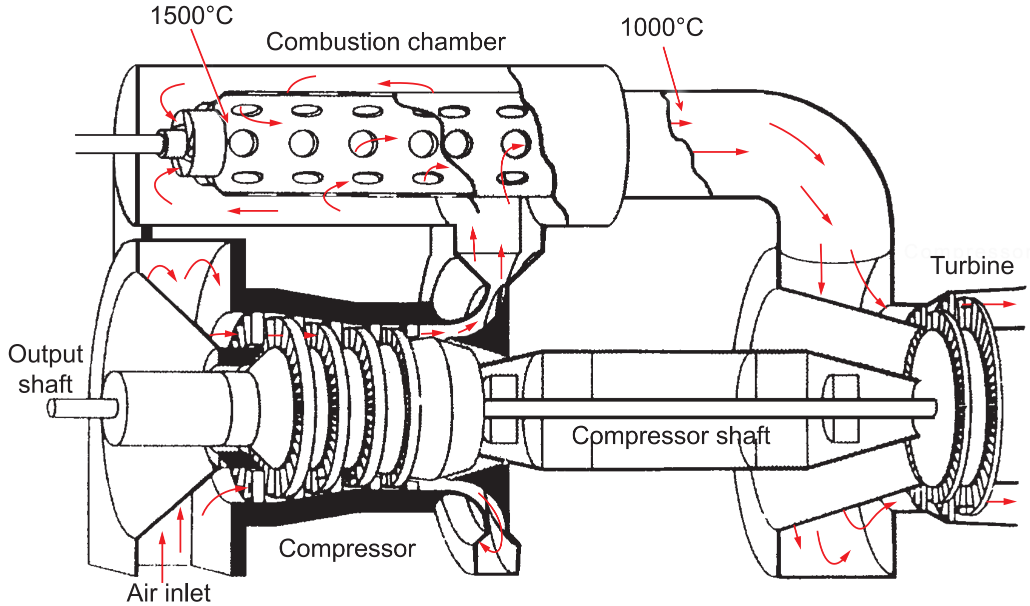
A major drawback of gas turbines is that they are limited to clean, liquid, or gaseous fuels. They cannot burn solid fuels.

NO_X Emissions

NO_X emissions are high due to the high combustion temperatures and short residence time. These are major environmental concerns.

Figure 12 shows the typical temperatures found in a gas turbine. Note that this machine is a simple, open-cycle, single-shaft gas turbine. The turbine blading drives both the compressor and the load on the same shaft.

Figure 12 – Gas Turbine, Typical Temperatures



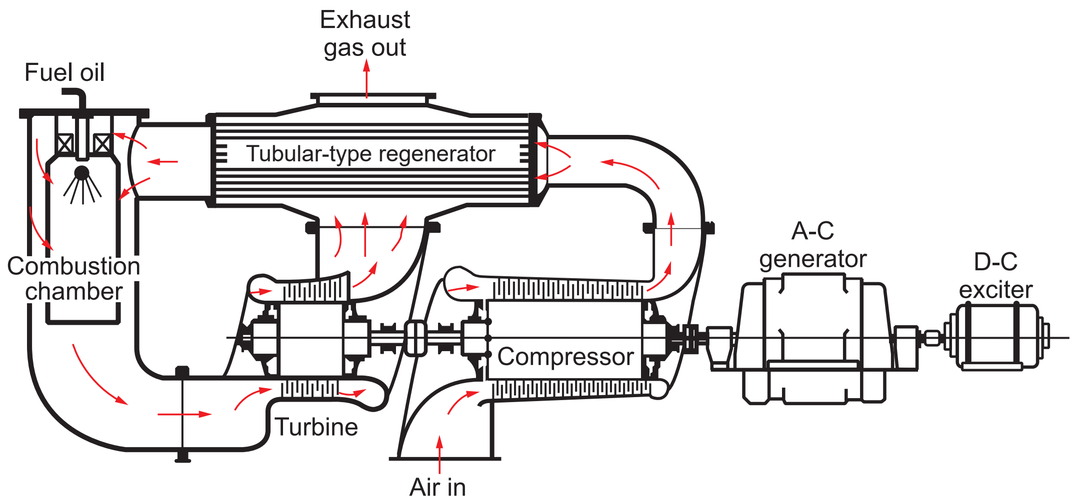
Objective 3

Describe regeneration and combined steam-gas turbine operating cycles.

Regeneration

It was stated earlier that a simple gas turbine was one without reheaters or **regenerators**. Figure 13 shows a gas turbine layout that includes a regenerator.

Figure 13 – Regenerative Gas Turbine



The purpose of a regenerator is to improve the cycle efficiency by recovering some of the heat that would otherwise pass to waste with the exhaust gases. The regenerator is placed in the airflow, after the compressor and before the combustion chamber. Because of this placement, exhaust gases from the turbine heat the compressed air before it enters the combustion chamber.

The compressor works most effectively with cold air. The heat recovered from the exhaust gas reduces the amount of fuel required to produce the same load.

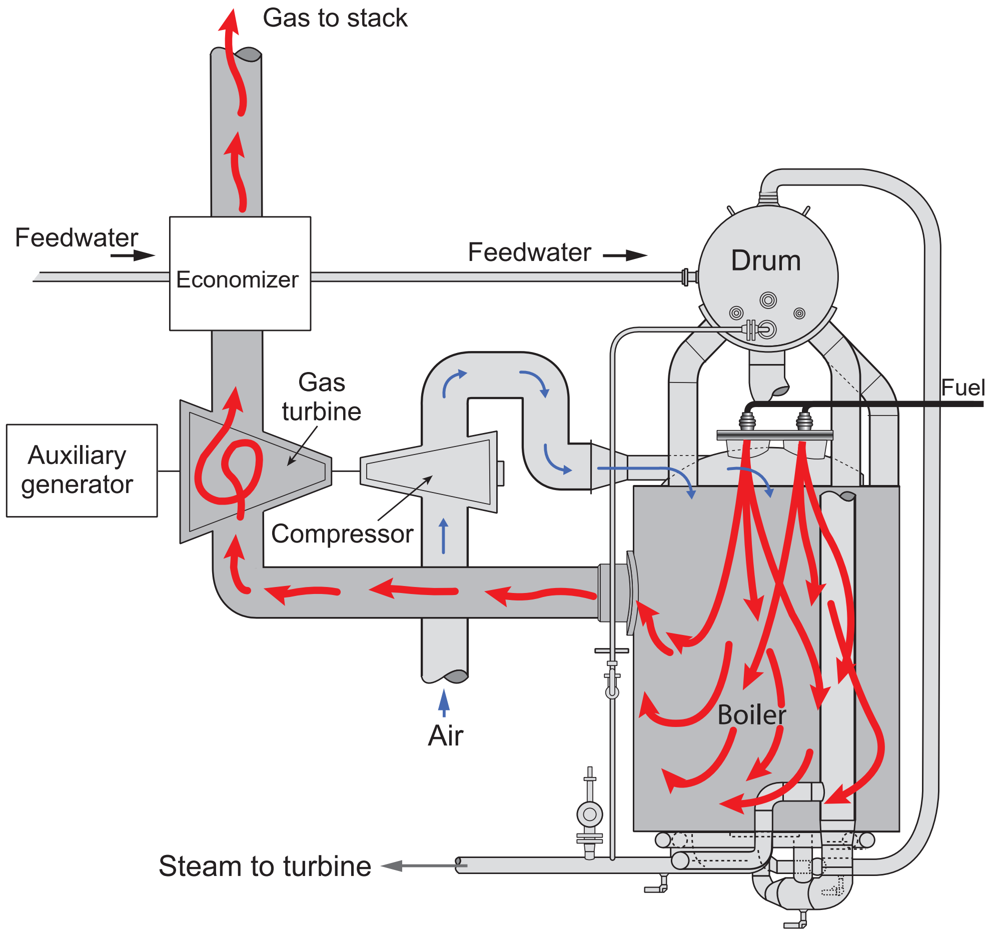
Combined Steam-Gas Plants

Gas turbines can be used in conjunction with steam boilers in various ways. One way is to pressurize the boiler furnace with the air leaving the compressor (pressurized fluidized bed combustion). Then, the hot gases pass from the boiler through a gas turbine to drive the compressor, and the alternator. In this arrangement, the gas turbine contributes to the total plant capacity, and the overall plant economy is improved.

The high furnace pressure at which a boiler of this type operates, allows for a reduction in boiler size. This combined arrangement of steam system and gas turbine is commonly referred to as a combined cycle. Thermodynamically, it is a more efficient use of fuel with regards to steam and electrical power generation.

Figure 14 shows a combined steam-gas boiler plant arrangement.

Figure 14 – Combined Steam Boiler-Gas Turbine Plant



(Courtesy of Foster Wheeler Inc.)

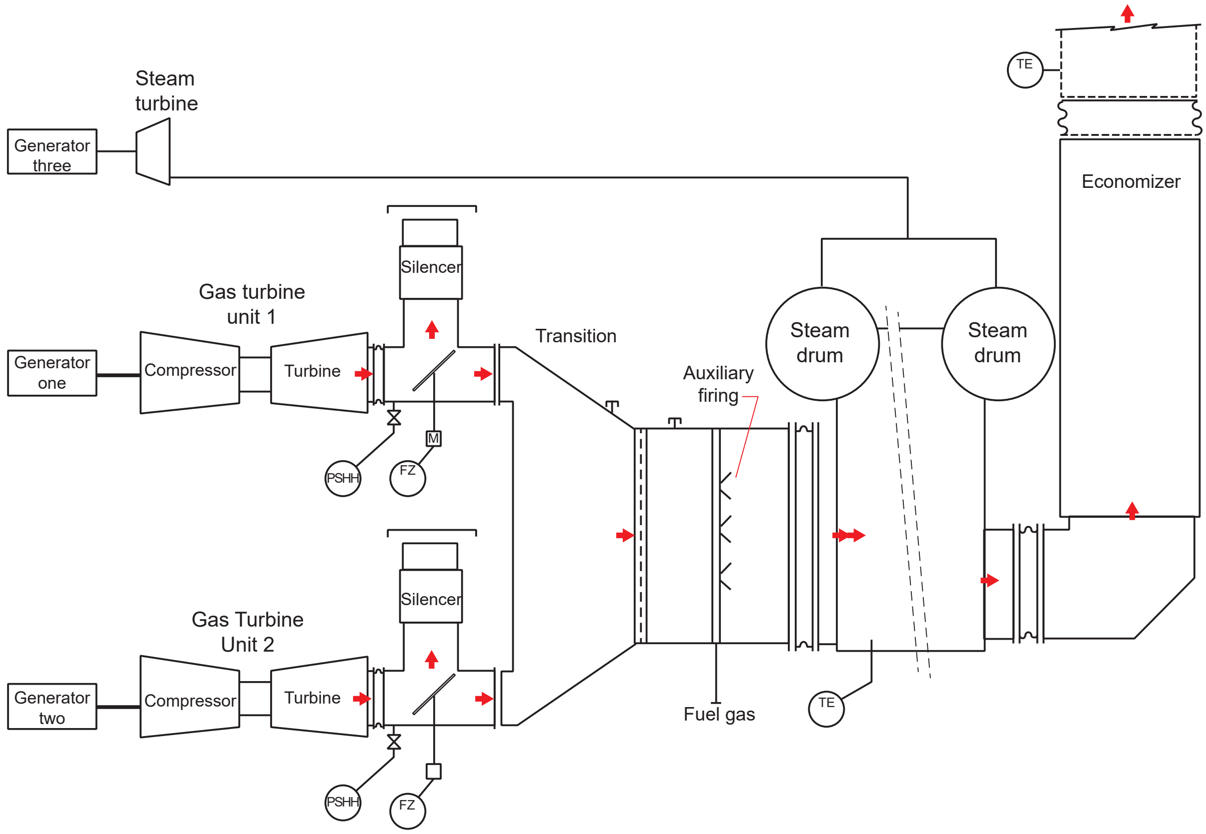
More commonly, large combined cycle systems can have separate gas turbine units of up to 300 MW attached directly to an alternator. Other cogeneration designs place the boiler after the gas turbine, so that turbine exhaust heat is recovered in the boiler.

Since exhaust from the gas turbine contains considerable excess air and oxygen, the exhaust stream can be further reheated with additional fuel, much the same as an after-burner. The extra fuel is injected between the power turbine and the steam boiler. This superheated exhaust then passes through a **heat recovery steam generator (HRSG)**.

Often, the steam generated in the boiler is supplied to a steam turbine, which itself drives an additional electrical power generator. This is also a combined cycle plant, since it uses both the gas turbine and steam plant thermodynamic cycles to produce power. These combined cycle plants can be built in multiple sets, providing 300 – 1500 MW of electrical power at over 60% efficiency. They require clean fuel (gas or oil), and can be started up and shut down quickly. They are excellent to use for short term maximum power ("peak") demand.

Figure 15 shows a typical combined cycle arrangement. It has two gas turbines and one steam turbine, each driving an alternator.

Figure 15 – Combined Cycle with Heat Recovery Steam Generator (HRSG)



Objective 4

Describe the key elements of gas turbine startup, operation, and auxiliaries.

Gas Turbine Operation

Operating conditions vary widely from location to location, and from plant to plant. Operators should understand how ambient temperatures and atmospheric pressure affects the operation and performance of gas turbines.

Air temperature changes have an inverse effect on air density. For a given mass of atmospheric air, an increase in temperature produces a decrease in density. The opposite is also true. Barometric pressure has a direct effect on air density. Air with high barometric pressure is denser than air with low barometric pressure. A change in either temperature or barometric pressure dramatically change the output of a gas turbine. This is because gas turbine power output depends on the mass of air flow, which is dependent on density. When designing this turbine, local atmospheric conditions are considered by sizing the equipment for possible density fluctuations.

On Track

Changes in atmospheric pressure and temperature affect the performance of gas turbines, internal combustion engines, and boilers.

During startup, fuel admission and ignition sequences are programmed automatically as a function of the compressor inlet temperature, compressor discharge pressure, and engine speed. Fuel control systems vary with the type of fuel used. Fuel systems use natural gas, liquid, or gas-liquid dual fuels. Clean gaseous fuels are preferred. A fuel system includes pumps, booster pumps, fuel filters, a fuel control valve, a fuel shutoff valve, a fuel nozzle for each combustor, and a fuel governor actuator.

Gas Turbine Starting Methods

Starting a gas turbine can be either manual, semiautomatic, or automatic:

Manual: The operator starts all auxiliary systems, and raises the gas turbine RPM to the minimum governor setting.

Semi-automatic: The operator only starts the auxiliary systems. The gas turbine is raised to the minimum governor setting automatically.

Fully Automatic: The operator pushes a start button. The turbine starts, and follows a timed procedure.

Typical Gas Turbine Startup

Gas turbines operate under a large variety of conditions. A turbine startup procedure can be different for every installation. This text gives only one example of a gas turbine plant startup.

An automatic gas turbine might be started as follows:

1. The operator pushes a start button.
2. The engine starter begins to rotate the engine.
3. The engine RPM and oil pressure begin to increase.
4. At approximately 20% of the maximum engine RPM, a signal starts the ignition and opens the fuel shut-off valve.
5. The engine ignites and continues to accelerate at a maximum rate, in order to reach the running speed in the shortest possible time.
6. At 50% of the maximum RPM, the ignition turns off and the starter motor disengages.
7. If 50% RPM is not reached in 60 seconds, cranking is aborted.
8. The engine reaches minimum operating speed and stabilizes. If engine is not up to speed in 90 seconds, startup is aborted.

Gas Turbine Load Control

Governing a gas turbine generally depends on the load-shaft speed sensitivity governor, much like that of a steam turbine. The governor obtains the signal from the turbine shaft speed, and either increases or decreases the fuel flow to the combustor. A reduction of fuel flow will slow the turbine. An increase will speed up the turbine.

Flyball type governors are widely used with small turbine installations to control the speed. However, large gas turbines are fitted with several governors, far more sophisticated than the flyball type.

Gas turbines must also have overspeed trip devices. If the turbine speed exceeds a pre-determined RPM, fuel is cut off immediately, which brings the turbine to rest.

Typical Gas Turbine Alarm Signals

Depending upon the type of installation, the following are warning points that indicate possible problems:

High vibrations of various parts of the gas turbine system: Any vibration level that exceeds a preset limit will send a warning signal to the operating panel. Vibration monitoring devices are also programmed to close the fuel supply to the gas turbine, if the vibration exceeds preset limits.

Generator stator high temperature: A high stator temperature indicates an impending cooling system problem. If preset values are exceeded, the fuel shut-off device is initiated.

Ignition tripped: A tripped ignition system leads to a non-starting situation. The reasons for no ignition must be corrected. Otherwise, a fire or explosion can result.

High differential pressure air intake: This is an indication of dirty air inlet filters.

Low lubrication oil pressure: Any abnormal lubrication oil pressures are indicated on the operator alarm panel. If the preset safety limits are exceeded, the turbine will be shut down by closing the fuel supply.

Gas Turbine Auxiliary Systems

Gas Turbine Starting System

Gas turbines require a separate starting system. The system used could be an electric motor, an internal combustion engine, or high-pressure air directed at the turbine blades. The startup sequence usually includes periods of cranking, followed by purging, firing, acceleration, and acceptance of load. Generally, about 25 to 50% of the final RPM is required before the turbine becomes self-supporting.

Lubrication Oil Pumps

Gas turbines require lubrication. Generally, gear pumps are preferred, directly driven by the shaft, similar to that of the steam turbine. A rotating gas turbine ensures continuous lubrication. If the RPM of the turbine fails to turn below a preset RPM, then an auxiliary pump will supply the required lubricant.

Auxiliary lubrication oil supply is essential. It supplies lubrication to the bearings, and for cooling of the bearing. Auxiliary pumps may be driven by an electric motor, supplied with an emergency power source. Another method to drive the pump is with an internal combustion engine, directly connected to the auxiliary pump.

Combustor Temperature Control

The gas turbine process is controlled by adjusting the fuel flow to the combustor. Since this very high temperature cannot be measured directly, the temperature is calculated from both the gas turbine and the compressor discharge temperature. The values obtained are used to control the temperature, and to protect the system against temperatures above the manufacturer recommendations.

Fuel Pumps

The type of liquid fuel utilized for a gas turbine determines the type of pump employed. Fuel pumps are generally volumetric, or of the centrifugal type. Gas compressors may be required if the turbine operates on natural gas.

Air Intake Filtration

In the case of an open system, atmospheric air is the working fluid, and it must be clean. Generally, a two-stage arrangement, comprised of primary and secondary filtration systems, is used.

Compressor Blade Cleaning

It is impossible to avoid the intake of some materials that may be present in the air stream. These materials will eventually come to rest on the compressor blading. For this reason, most compressors are fitted with a blade cleaning system. The cleaning media most commonly used is a sort of detergent, which is injected into the air intake of the LP compressor.

Anti-Icing

When gas turbines operate in cold climates, an anti-icing system is required. This method takes hot air from the compressor section, and reintroduces it into the compressor inlet section. Since this is part of the air bleed, capacity is reduced in proportion to the air being bled off.

Fire Protection

Gas turbines are protected by automatic fire suppression systems. In the event of a fire, pressurized halon or carbon dioxide nozzles are activated by temperature-sensitive relays. Automatic firefighting equipment may be over-ridden manually. During such an event, fuel valves to the combustors are closed and audible alarms are activated. The gas turbine is usually wired to trip in the event of a fire or other dangerous circumstances, such as severe vibrations and overspeeding.

Gas Turbine Maintenance

Maintenance procedures for gas turbines may be divided in two groups:

Major overhaul: A major overhaul involves a total strip down of the gas turbine. This is done to inspect, clean, and repair the bearings, the air compressor, the turbine rotors and blading, the control equipment, the gearboxes and coupling, the combustor and ignition system, the fire suppression equipment, and more.

Short shutdowns: During a short shutdown, inlet air filters may be inspected, cleaned, or replaced. Fouled compressor blading may be washed. Individual bearings may be replaced. Other activities that do not involve major disassembly and extensive periods of time may also be scheduled.

Aging

The power output and efficiency of the gas turbine will decrease during its life span. Even a lengthy out-of-service period may shorten its life span. It is assumed that gas turbines experience a loss of 0.5% in power and efficiency for every 1000 hours of service.

The following should be observed or checked for aging or maintenance:

- Increased roughness of the blading caused by corrosion. This may be due to impurities present in the fuel.
- Increased roughness on the turbine blades caused by oxidation.
- Rust on rotors, housing and its piping; scratches on vanes, blades, and labyrinth seals.

Chapter Summary

This chapter identified the major components of a gas turbine. It also covered:

- The steps to start and operate a typical gas turbine.
- How to distinguish the operating characteristics of a gas turbine compared to other types of prime movers.
- The purpose of a regenerator in a gas turbine system.

Cogeneration facilities are now found in the industry, and were introduced in this chapter. A brief description of how these systems work or operate was discussed.

CHAPTER 5

Internal Combustion Engines

Learning Outcome

When you complete this chapter you should be able to:

Describe the application, construction, and operation of internal combustion engines.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Discuss the fuels used in internal combustion engines.*
2. *Describe the working cycles of the 4-stroke and 2-stroke spark ignition engines.*
3. *Describe the working cycle of the 4-stroke compression ignition (diesel) cycle.*
4. *Describe the construction of basic spark and compression engines.*
5. *Explain the basic operating considerations for diesel engines.*

Chapter Introduction

The Power Engineer of today frequently comes into contact with internal combustion engines. They are used as small standby or emergency generating units in many power plants. These engines may also be used to drive auxiliary equipment, such as fire pumps.

The term "internal combustion engine" applies to all engines that burn fuel in the engine cylinder. Compare this concept with the steam engine; steam does the work in the engine cylinder, but the transfer of the chemical energy in the fuel into useful heat in the steam takes place in the boiler.

To describe an internal combustion engine type, it is necessary to specify the fuel used and the working cycle. In addition, for each type of fuel and cycle there are different possibilities for the method of ignition, the method of fuel delivery to the cylinder, and the way in which the output of the engine is governed. Furthermore, a particular engine will be quoted on its number and arrangement of working cylinders and power output.

Objective 1

Discuss the fuels used in internal combustion engines.

Fuel Used

The most common fuels used by **internal combustion engines (ICE)** are:

- Natural gas
- Gasoline
- Light **fuel oil**
- Heavy fuel oil

Propane's use dropped for a while, due to rising fuel prices and problems in getting emission control modules to react to its unique combustion conditions. Interest in propane is on the rise again, due to modern computerized control modules, better fuel efficiency, and lower carbon emissions.

Natural Gas

Natural gas is generally considered an environmentally clean alternative to other hydrocarbon fuels. Compressed methane extracted from natural gas is stored, usually in cylinders, for use in mobile engines. Stationary engines that burn this fuel are commonly in use where natural gas is readily accessible and can be piped in. They are often used as the drive units for gas compression machinery.

Natural **gas engines** can work on a two or four-stroke cycle, Ignition can be supplied by a hot ignition tube or electric spark. **Governing** is by throttling of the fuel.

Gasoline

Gasoline is a liquid consisting primarily of hydrocarbons. It is also enhanced with benzene or iso octanes to increase the octane rating. This rating is a measure of the fuel's resistance to premature detonation which causes engine knock.

The gasoline engine is a high-speed type, and works on either a two- or four-stroke cycle. Ignition is by spark. The fuel is in liquid form and vapourizes when it is drawn or injected into the engine cylinder. Governing takes place by throttling the resulting air/fuel mixture. Most modern engines use fuel injected directly into the intake manifold or the cylinder.

#1 Light Fuel Oil

Engines that use light oils, such as kerosene, are not as common as gasoline engines. The cycle used may be two-stroke or four-stroke. The fuel is sprayed into a vapourizer, heated by the exhaust gases, and then drawn into the cylinder together with air. Governing is by throttling of this air/fuel mixture. Most modern engines now use direct fuel injection into the intake manifold.

#2 or #3 Fuel Oil

Heavy oil refers to fuel oils with a higher viscosity and specific gravity. These oils are used in high compression engines. These may be low speed or high speed, two-stroke or four-stroke cycle.

The fuel ignites due to the high temperature developed during compression of the combustion air charge. For this reason, this engine is called a "compression ignition engine."

To govern the output of this engine, the fuel quantity injected is varied. An increase in the amount of fuel injected increases the power output. A reduction of fuel decreases the power output.

Since the quantity of air drawn is constant for a given engine speed, the air/fuel ratio changes with each load setting. This is quite different from the gasoline engine, where the quantity of fuel-air mixture is varied.

Objective 2

Describe the working cycles of the 4-stroke and 2-stroke spark ignition engines.

Working Cycle

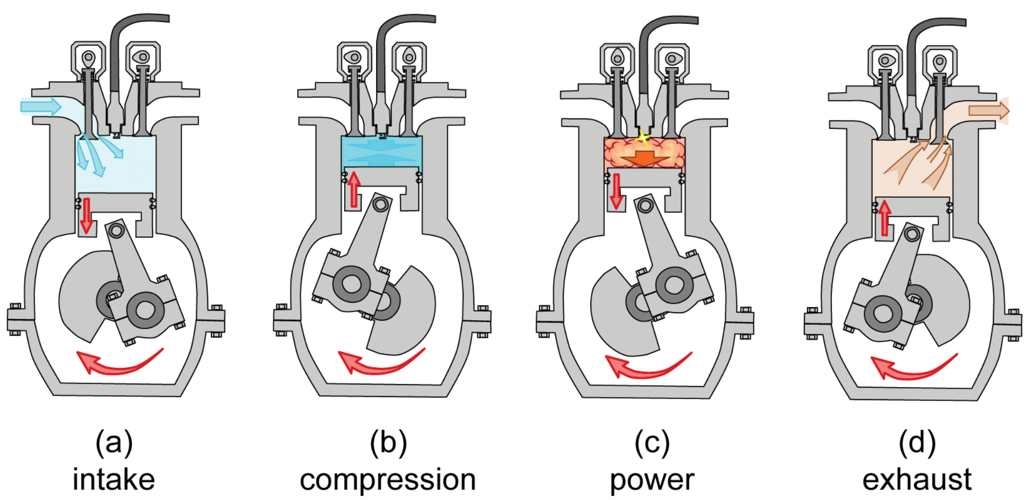
Internal combustion engines can be grouped according to the number of strokes in a working cycle. Working cycles for internal combustion engines include two-stroke and four-stroke cycle spark ignition, as well as two-stroke and four-stroke cycle compression ignition.

Four-Stroke Spark Ignition Cycle

The four-cycle engine, properly called the "four-stroke cycle" engine, was developed before the two-stroke engine. A **stroke** is the complete movement of a **piston** in one direction, corresponding to one-half revolution of a **crankshaft** (refer to Figure 4). Each cylinder is fitted with two or more **poppet valves**, for intake and exhaust. These valves are kept closed with springs. At a precise moment, the valves are opened by the lobes of a **camshaft**, which is geared to the crankshaft.

Figure 1 shows that the **four-stroke cycle engine** requires four strokes, or two complete crankshaft revolutions, to produce one power stroke. The following describes each stroke in the cycle:

Figure 1 – Four-Stroke Cycle Gasoline Engine Operation



a) **Intake Stroke**: The inlet valve is open while the piston moves down. This draws a mixture of gasoline and air into the cylinder.

b) **Compression Stroke**: The inlet valve is closed and the piston moves upward, which compresses the mixture in the combustion chamber. Near the upper end of this stroke, the spark plug is timed to ignite the mixture.

c) **Power Stroke**: The mixture burns and generates a high pressure which forces the piston downward. This downward motion forces the crankshaft to turn and produces useful power. Near the end of this stroke, the exhaust valve opens to begin the removal of burned gases from the cylinder.

d) **Exhaust Stroke**: The exhaust valve remains open while the piston moves upward. This pushes out most of the remaining burned gases in preparation for the next intake stroke.

Consider, for example, a four-cylinder engine. This engine has four pistons connected to the same crankshaft. All four of the strokes described above happen at the same time, but in different cylinders. Therefore, one of the four pistons is always in a power stroke turning the crankshaft.

Refer to Figure 4. The four-stroke engine is usually lubricated by oil in its **crankcase**, which is either pumped under pressure to the bearing surfaces, or is splashed onto them by rotation of the **crank webs**. The **piston rings** limit the amount of oil entering the combustion chamber, and keep the carbon deposits to a minimum.

The four-stroke engine gives good fuel economy, good control at all speeds, and high torque at low speeds. However, it is more mechanically complex and heavier than a two-stroke engine of the same power rating.

Two-Stroke Spark Ignition Cycle

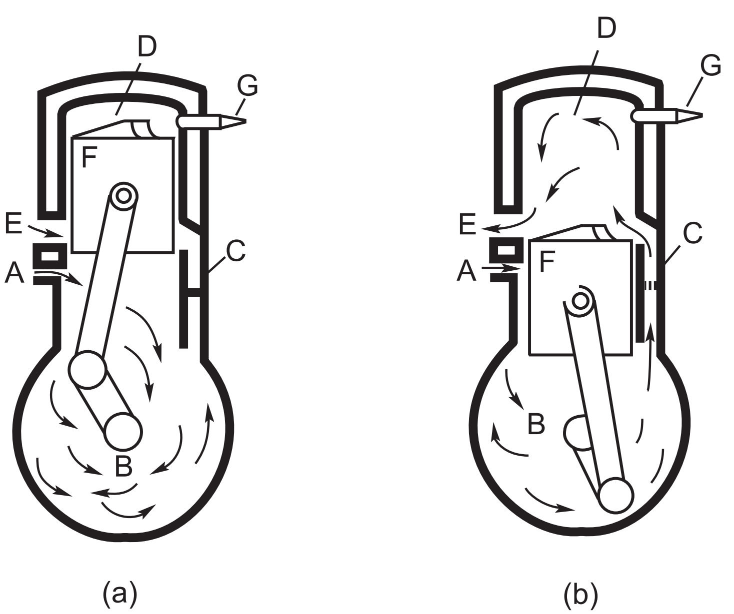
The **two-stroke cycle engine** is noted for its simplicity. This engine (see Figure 2) functions by utilizing three openings, or "ports," in its cylinder wall. The openings are covered or uncovered by the piston. Thus, there are no poppet valves and no camshaft.

The intake and exhaust functions happen simultaneously during only a part of one stroke. For this reason, the two-stroke engine produces a power stroke for every crankshaft revolution.

Refer to Figure 2(a). The upward stroke of piston F compresses a mixture of gasoline vapour and air into the combustion chamber D. The same piston stroke also creates a partial vacuum in crankcase B, which draws in the next mixture charge from the **carburetor** through port A. Near the upper end of the stroke, spark plug G is timed to ignite the compressed mixture.

In Figure 2(b), the pressure in the cylinder, which results from fuel combustion, forces piston F downward on its power stroke. This closes intake port A, and compresses the new mixture charge in the crankcase B. Near the lower end of this stroke, the piston uncovers exhaust port E, which releases cylinder pressure and discharges most of the burned gases.

Figure 2 – Two-Stroke Engine Operating Principle



Further piston movement then uncovers the transfer port C. This allows the new compressed mixture in the crankcase to flow upward into the combustion chamber. It then assists in pushing the exhaust gases through exhaust port E. The head of the piston is usually shaped to direct the flow of new mixture upward. This helps to get the maximum displacement of exhaust gas with minimum loss of new mixture out of the exhaust port.

The two-stroke engine is lubricated by thoroughly mixing a measured quantity of special lubricating oil with the gasoline in the tank. When this mixture passes through the carburetor, the gasoline is vapourized. The oil is carried through as an oil fog, and it lubricates all parts of the engine during its passage. Newer two-stroke engines are oil-injected.

Theoretically, the two-stroke engine should produce twice as much power as a four-stroke of the same size and speed, but it does not. This is because it is less efficient at exhaust gas **scavenging** (the removal of combustion products from the cylinder).

Two-stroke spark ignition engines find application where maximum power with minimum size and mass are required. They operate best at high engine speeds.

Objective 3

Describe the working cycle of the 4-stroke compression ignition (diesel) cycle.

Almost identical diagrams could be drawn to illustrate the operation of **diesel engines** (compression ignition); both two- and four-stroke cycles can be used. The major differences are:

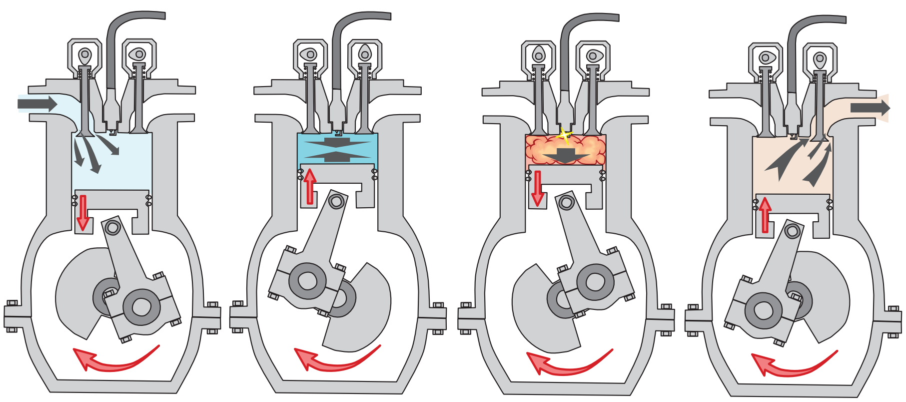
a) Fuel is injected, at high pressure, directly into the engine cylinder in a finely atomized form.

b) Ignition takes place without the aid of a spark.

Four-Stroke Compression Ignition Cycle

The four strokes in sequence are suction, compression, power, and exhaust. Figure 3 shows the operation of a four-stroke diesel. The following describes each stroke in the cycle:

Figure 3 – Four-Stroke Cycle Compression Ignition Engine



a) **Suction Stroke**: On the suction stroke, the inlet valve opens just before the piston reaches the **top dead centre** position. The exhaust valve closes just after the piston reaches top dead centre. These actions allow a charge of air to be drawn into the cylinder through the inlet valve as the piston descends.

b) **Compression Stroke**: After the piston has passed the **bottom dead centre** position, the air inlet valve closes. Compression begins as the piston rises. Shortly before top dead centre, fuel injection begins. Meanwhile, compression of the air will have raised its temperature to between 540 and 650°C, and its pressure in the range of 2800 to 4200 kPa. Under these temperature and pressure conditions, the fuel will ignite almost as soon as it enters the cylinder and mixes with the hot air. There is a momentary increase of temperature and pressure as the fuel burns and the power stroke commences.

c) **Power Stroke**: The hot gases of combustion expand and force the piston downwards. Before it reaches bottom dead centre, the burning gases have expended their energy. The exhaust valve opens to allow the gases to escape from the cylinder.

d) **Exhaust Stroke**: As the piston again ascends in the cylinder, the remaining exhaust gases are forced out through the open exhaust valve. Just before the piston reaches the top dead centre position, the inlet valve opens. The whole cycle of events then repeats.

Two-Stroke Compression Ignition Cycle

Two-stroke cycle compression ignition engines, like two-stroke spark ignition engines, have problems with exhaust gas scavenging. As well, these engines do not have an induction stroke, and cannot draw in adequate combustion air. For more complete scavenging, and to provide combustion air, it is common to use some means of forced induction. The most common methods of air induction and exhaust scavenging are superchargers and turbochargers.

Two-stroke compression ignition engines are still being used. They follow the same basic principle as the two-stroke spark ignition engines.

Objective 4

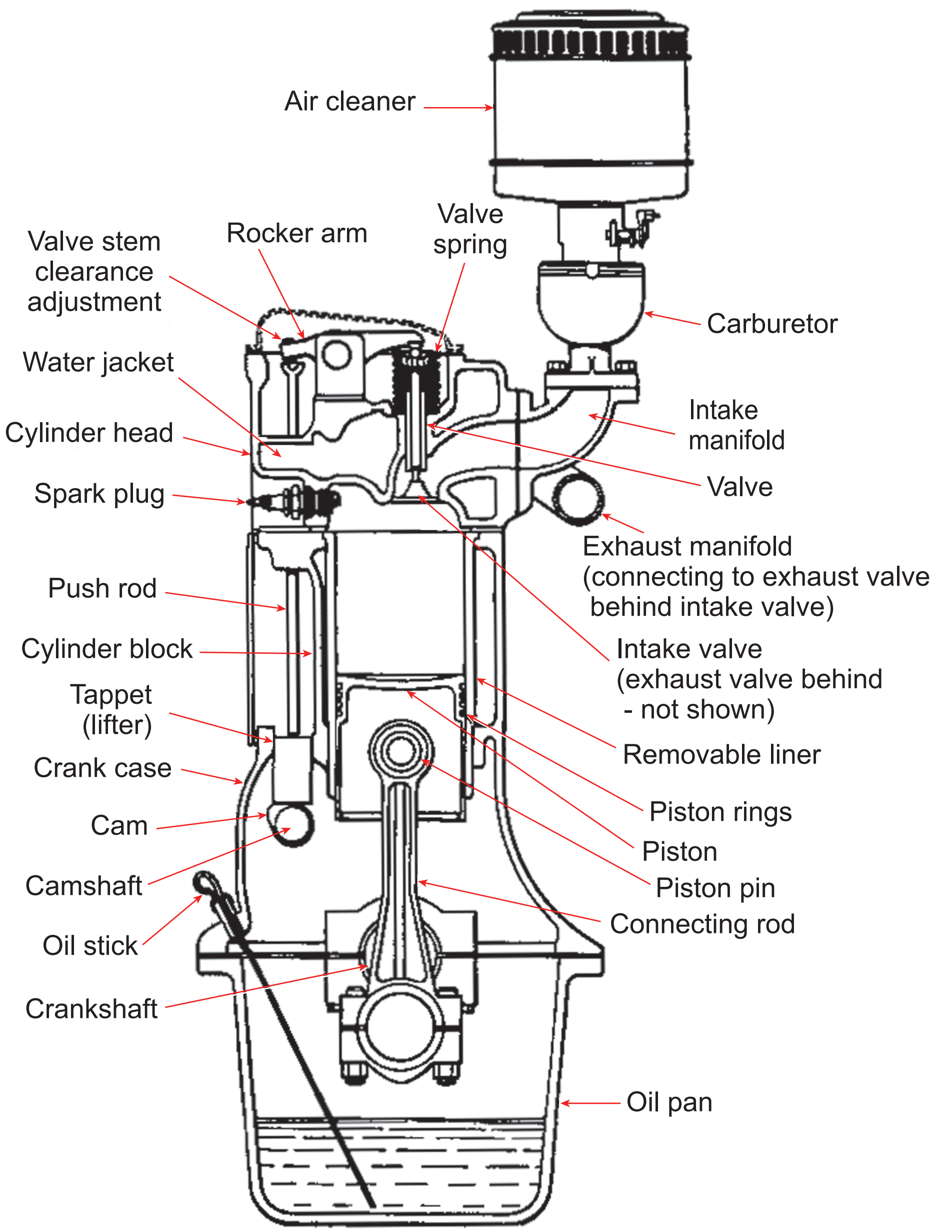
Describe the construction of basic spark and compression engines.

Basic Engine Construction

Spark Ignition Engine

Figure 4 is a schematic of a four-stroke gasoline engine. This engine operates with spark ignition; thus, it has a carburetor to vapourize the fuel. Although only one cylinder is shown, an engine may have four, six, eight, or even twelve cylinders.

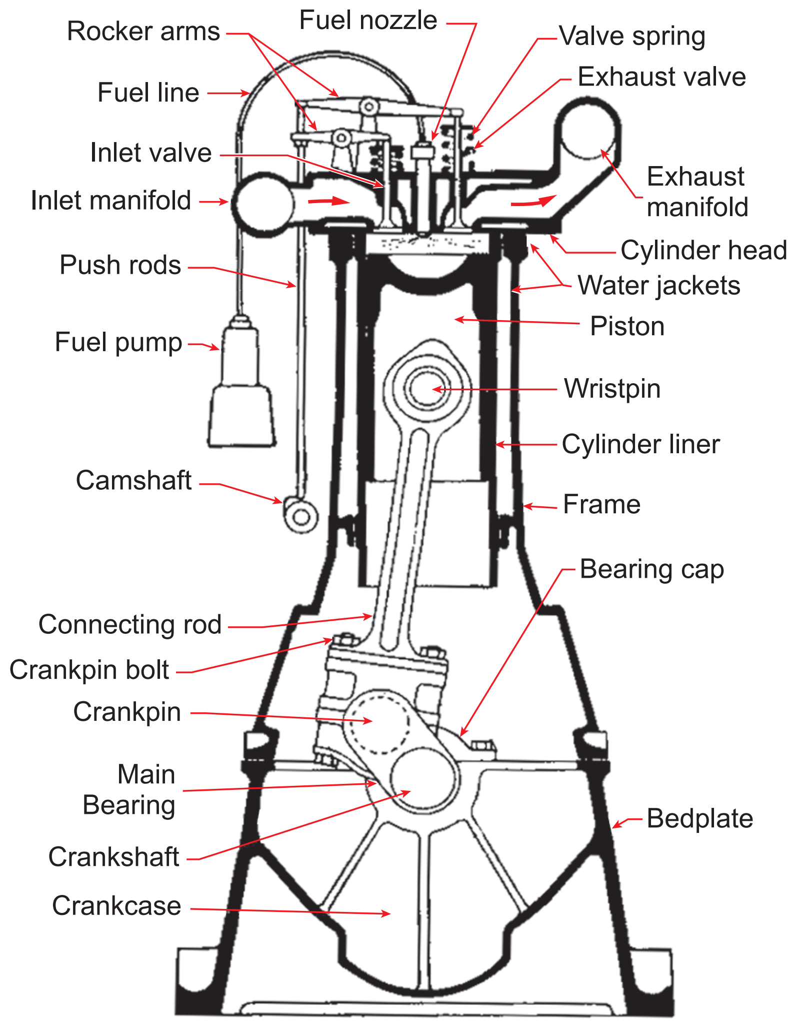
Figure 4 – Schematic Diagram of Four Stroke Gasoline Engine



Four-Stroke Diesel Engine

Figure 5 shows the basic construction of a four-stroke diesel engine. These engines use compression ignition, and have no carburetor. Fuel oil, delivered to the cylinder via a **fuel injector** pump and fuel injector nozzle, mixes with air in the cylinder. Depending on engine size, the frame and bedplate will be of either cast or welded construction. The frame carries the cylinder liners. The illustration shows only one cylinder because it is an end view, but in fact, there may be four, six, eight, twelve, or sixteen cylinders.

Figure 5 – Parts of a Four-Stroke Diesel Engine



The **cylinder head** closes one end of the cylinder, and the moving piston closes the other end. In Figure 5, the piston is approaching top dead centre, with both the inlet and exhaust valves closed; fuel is being injected into the cylinder through the fuel injector nozzle.

The cylinder head holds the fuel injector nozzles, the valves, and their operating rockers. The head also has flow passages that connect to the inlet and exhaust manifolds. The cylinder and head both have water jackets through which cooling water circulates.

The moving parts (pistons, **connecting rods**, **crank pins**, crankshaft, and main bearings) are very similar to those of a steam engine. The crankshaft drives the camshaft via a connecting gear, chain, or belt. The camshaft operates the valve push rods by forcing them to ride up over the lobes on the cams. Each individual push rod is operated by its own cam. The push rods, in turn, operate rocker arms, which transmit their movement to the valves. The fuel injector pump supplies high-pressure fuel to the fuel injector nozzle. The pump is also driven from the camshaft, in this case.

Note that the spark plug, high-voltage ignition coil, and **distributor** of the spark ignition engine are absent from Figure 5.

The cylinder head, liner, and piston top form the combustion chamber, into which a charge of air is compressed to high pressure and temperature. Using a fuel injector and fuel injector pump, fuel oil is then introduced at a higher pressure to cause the oil to break into a finely atomized spray. The high **compression ratio** (as high as 25:1), and the resulting **heat of compression** produce the high-pressure, which produces spontaneous combustion of the fuel. The subsequent "explosion" of the air and fuel mixture in the cylinder creates force on the piston, which provides the driving force for the engine.

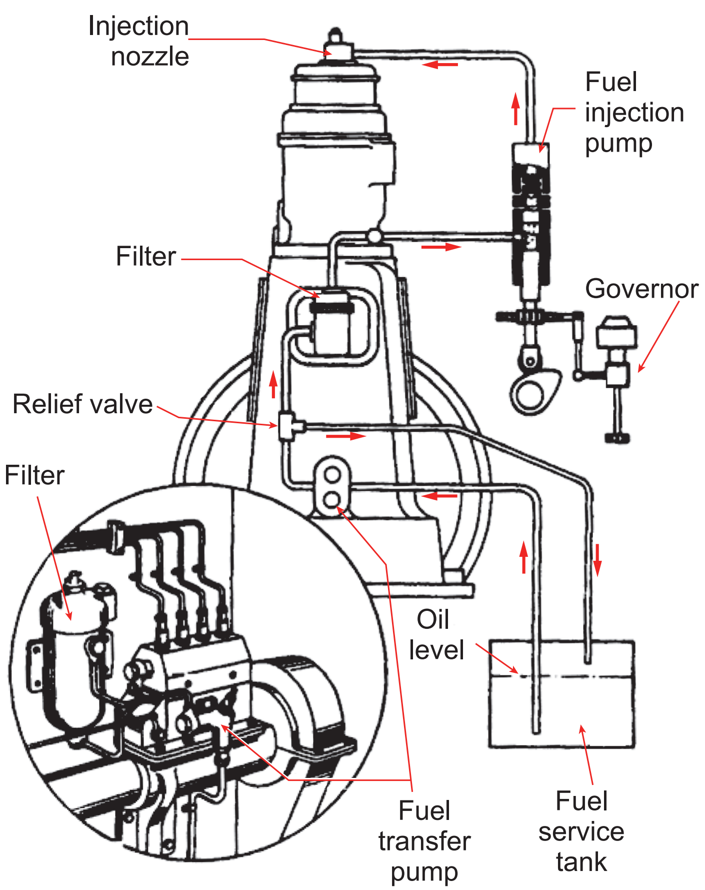
Figure 5 is an example of a typical four-stroke diesel engine. The details on individual engines will differ, but the general principles remain the same.

Figure 6 shows a solid injection system on a small engine. Each cylinder, or ram, of the fuel pump supplies one cylinder of the four-cylinder engine.

The section shows the operation in one of the cam driven plungers; the circled detail (bottom left of the image) shows the external appearance of the fuel pump.

The fuel oil for each cylinder is discharged through a fuel injection nozzle in the cylinder head which atomizes and directs the spray.

Figure 6 – Solid Injection Fuel System



Objective 5

Explain the basic operating considerations for diesel engines.

Diesel Engine Operation

The following are some operating notes for diesel engines. These notes must be considered as general remarks only. Where manufacturer instructions are available, they must be strictly adhered to.

Starting

The majority of stationary industrial type diesel engines are started with the use of compressed air; although, some smaller ones may have electric starter motors. In any case, the goal is to turn the engine crankshaft, which will then produce a high enough temperature in the air charge to ignite the fuel when it is injected into the cylinder.

Starting by compressed air may take one of two forms:

a) The air might be directed to an air motor to carry out the cranking.

b) The air might be led through a distributing device to one or more of the diesel engine's cylinders.

An air motor start is similar to an electric motor start. The starter engages the toothed or geared flywheel, and spins the crankshaft at a sufficient speed to start the engine. The air pressure for the starting motor is usually around 1400 kPa.

Diesel engines run some emergency generators, which must be up to speed within a minimum amount of time. These diesel engines are kept in a ready state, so they start quickly and reliably. Warm oil is continuously circulated. The coolant is kept at operating temperature, and is constantly circulated throughout the engine.

In the latter arrangement, a camshaft operates the air-distributing device. This device directs high-pressure air (about 2100 kPa) to each cylinder in turn on its power stroke through air-starting valves fitted in the cylinder heads. The air that enters the cylinders drives the pistons in a similar manner to that of steam driving a steam engine.

Before starting up, take special care to ensure that the fuel injection pump is primed to deliver fuel oil to the cylinders with the first revolution of the engine.

All lubricators (mechanical and otherwise) should be filled, the feeds opened, and the pumps primed to ensure prompt delivery of lubricating oil to all the moving parts. In circulation systems, the level of oil in the main reservoir should be checked. Where auxiliary pumps are used, they must be put into operation before starting the engine. Some engines have hand operated lubricating pumps fitted to the engine circulation system so that oil can be manually fed to the moving parts before the engine actually starts up. In such cases, these pumps must be used.

The starting air is now applied via the starting air control valve, through the distributor to those cylinders fitted with starting air valves, as mentioned earlier. After the engine turns on compressed air, fuel is injected into the cylinders by the fuel injection pump. The starting air is then shut off, and the engine operates by burning fuel in all cylinders. Both two-stroke and four-stroke engines may be started in this manner.

System Checks

While a diesel engine is operating, temperatures and pressures of the lubricating oil, cooling water, and the engine exhaust must be monitored. Care must be taken to prevent them from exceeding the manufacturer specifications.

One problem that can occur is that the pistons, cylinder walls, fuel injectors, and exhaust valves become coated with deposits. This may be caused by impurities in the fuel oil or the intake air. Carbon, as a result of incomplete combustion or the burning of lubricating oil, can also cause this problem. If these deposits are allowed to accumulate rapidly, frequent engine cleaning will become essential. Cleaning is always a costly procedure, so every effort must be made to avoid incorrect operating procedures.

A dirty, smoky exhaust, and excessively high exhaust gas temperatures are usually good indicators of incomplete combustion. This may result from any one of the following:

- Improper fuel injection
- Insufficient combustion air
- Unsuitable fuel
- Overloading
- Overcooling

Improper fuel injection may be due to:

- Worn or choked injector orifices
- Leaking nozzle or pump check valves
- Wear in the fuel pump or its driving cams and cam followers

Insufficient air will occur if excessive piston blowby permits the compressed air to leak past the piston during compression, or if inlet or exhaust valves fail to seat properly. Compression pressures should be checked at regular intervals, since a drop in this pressure will give warning of the development of these conditions. Two-stroke engines may suffer from improper scavenging due to partially clogged air vents or dirty air intake filters. Both of these will result in incomplete combustion.

Improper fuel oil selection may also cause incomplete combustion. The fuel may be too heavy to atomize correctly when injected into the cylinder, or it may have poor ignition qualities with not enough high volatility components. In cold climate areas, the fuel delivered must be appropriate for use at that time of year. Filling fuel oil tanks in the summer may be troublesome if the engine is to run in the winter. The "summer" fuel may not have the required pour point depressants to allow it to flow in winter, and may form gel in the lines. Additional additives may be necessary in the plant's holding tanks to allow for this.

Under some circumstances, overloading can be responsible for incomplete combustion. Cylinder overloading may occur even though the engine as a whole is not overloaded; this condition is indicated by a high cylinder exhaust temperature.

Engine Cooling

Engine cooling is particularly important for a diesel engine. Large diesel engines can be cooled with open cooling systems or closed cooling systems.

In an **open cooling system**, the water that circulates within the engine is sourced directly from a lake, river, ocean, cooling pond, or cooling tower sump. Because of this, the cooling water is full of environmental contaminants, including suspended matter, dissolved salts, and dissolved gases. These contaminants can cause scale and sludge that foul the engine cooling passages. This results in corrosion and overheating of the engine, which leads to premature engine failure. Therefore, open systems require considerable water treatment. Engines cooled with this system require frequent internal cleaning and descaling.

In a **closed cooling system**, the engine coolant is recirculated, through a water or air cooled heat exchanger. The system is initially filled with clean, pure water. Then, antifreeze and corrosion inhibitors are added. The coolant remains pure because it never directly contacts the environment outside the engine.

Figure 7 shows a typical diesel engine closed cooling system. It uses heat exchangers between the engine coolant (in green), and the water circulating in the cooling tower (in blue). The cooling system water is kept in a clean and treated condition. An additional shell and tube heat exchanger cools the lube oil. Control valves operate to maintain the temperatures of the engine coolant and the lube oil at their respective set points.

Figure 7 – Closed Cooling System with Shell and Tube Heat Exchangers

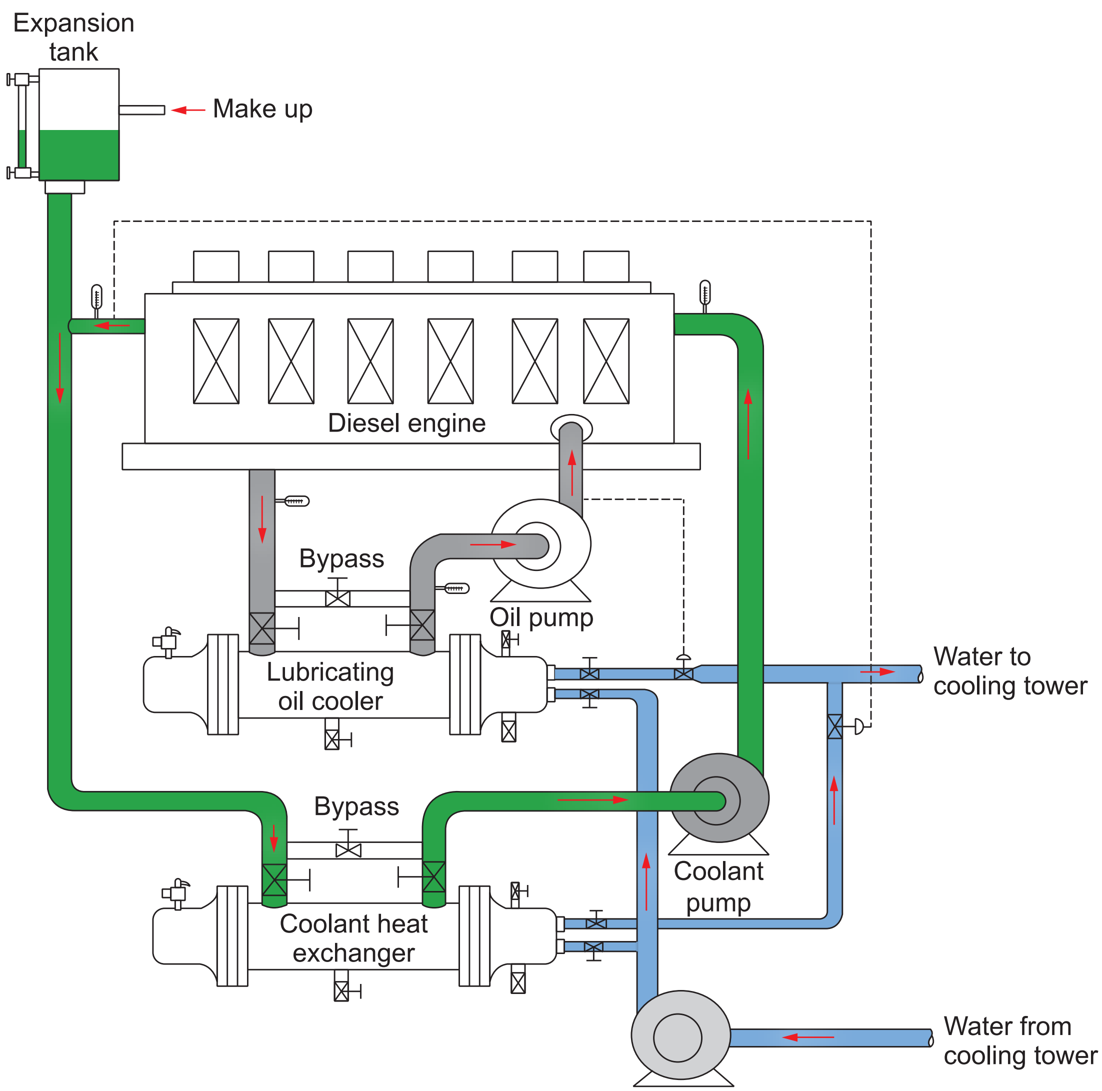
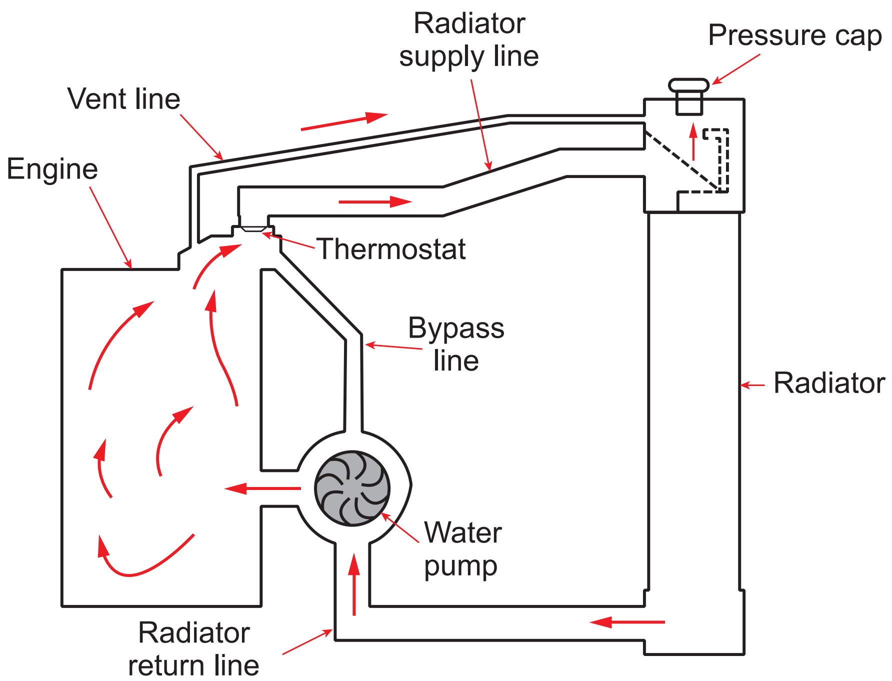


Figure 8 shows an air-cooled closed cooling system, similar to an automotive-style cooling system. This engine uses a large water-to-air heat exchanger, commonly called a radiator. A water pump circulates coolant from the radiator into the engine. The pump may be engine-driven, or driven by an auxiliary electric motor. During periods of light engine load, the engine outlet temperature is maintained by diverting some of the coolant flow back to the radiator through a thermostatically operated valve (called a thermostat). This thermostat is similar to the type used in cars and trucks.

Figure 8 – Closed System Air-Cooled Engine Cooling System



High-speed automotive type diesel engines run best with cooling water temperatures that are near boiling point. Larger industrial type engines run most efficiently with lower cooling water temperatures.

When coolant temperatures exceed the manufacturer's recommendation, the oil that coats the cylinder walls becomes less effective at sealing the clearance between the pistons and the cylinders. This encourages combustion gases to leak into the crankcase. When coolant temperatures are too low, the oil film becomes too thick and sluggish. This prevents proper distribution of the oil on the cylinder walls, and causes oil drag on the pistons. Both conditions result in cylinder deposits and reduced engine efficiency.

Figure 9 shows a diesel engine that powers a standby generator. Note the air discharge and radiator cooling fan on the left side of the photo. The louvres allow some heated air to return to the room during cold weather operation, with more air admitted through the wall of louvres on the right side of the engine. The electrical generator is in the bottom right of the photo.

Figure 9 – Diesel Standby Generator

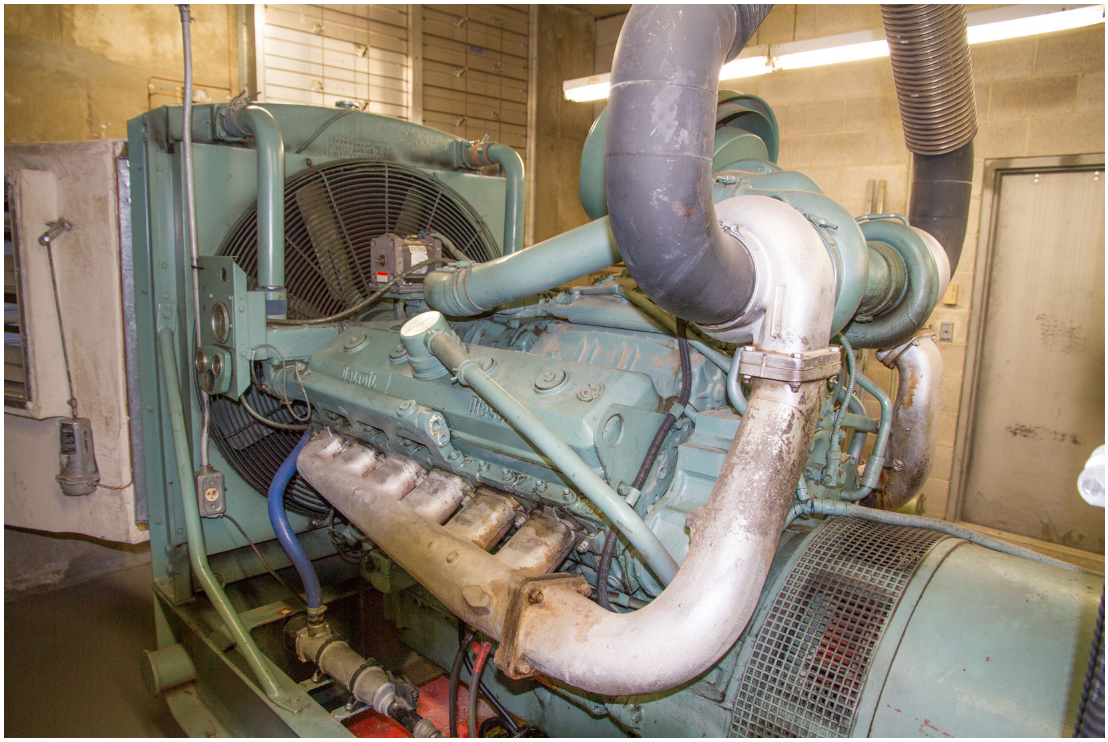


Figure 10 shows a three-cylinder diesel engine, used to drive a DC generator in a Power Engineering lab.

Figure 10 – Three-Cylinder Diesel Engine and Gen Set

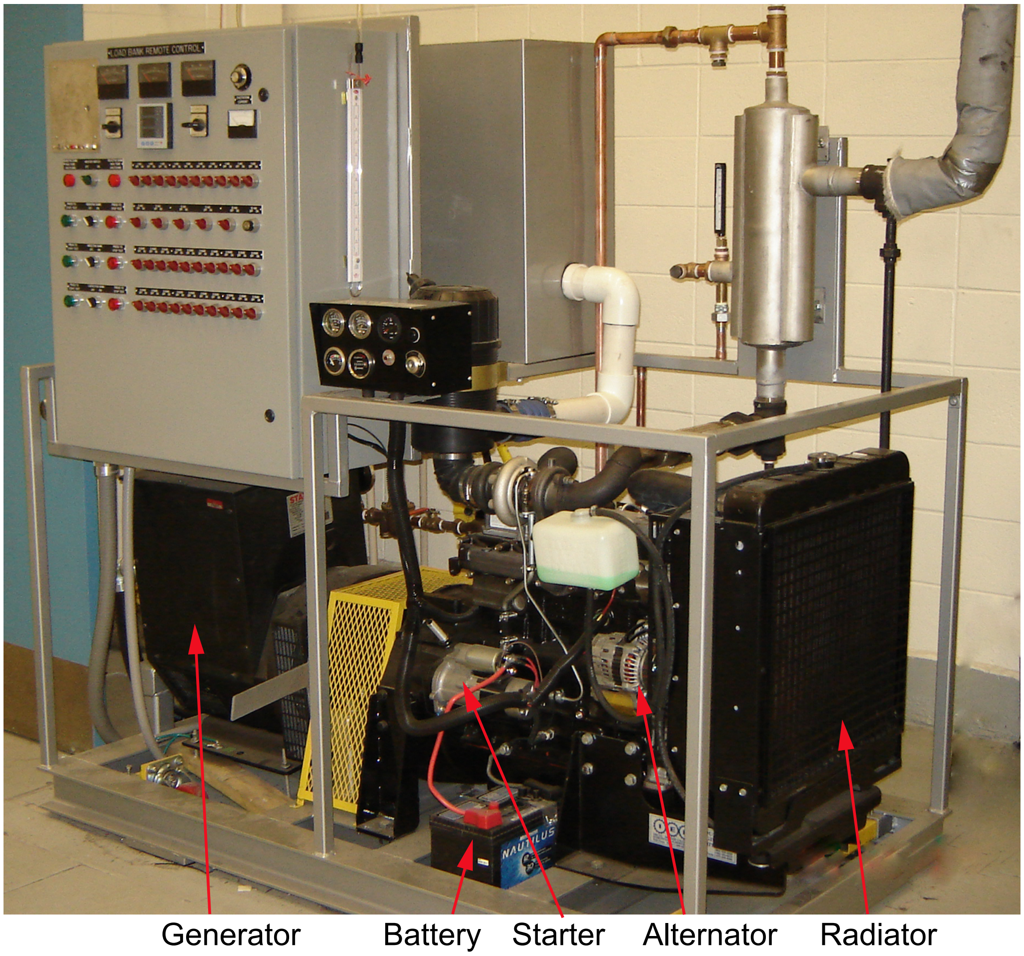


Figure 11 shows a diesel engine that is part of a cogeneration system. The generator is at the back of the engine. This engine also produces low-pressure hot water or steam from the exhaust gases, for heating purposes. The engine oil cooler, which is cooled by a closed loop glycol solution, is shown at the front of the engine.

Figure 11 – Diesel Engine as part of a Cogeneration System

Chapter Summary

Power Engineers are responsible for the internal combustion engines that drive emergency generating units, fire pumps, and other equipment.

The term "internal combustion engine" applies to all engines that burn fuel in the engine cylinder. It includes engines that burn natural gas, gasoline, and fuel oils. Each engine type has specialized features that suit the combustion of the particular fuel used.

Internal combustion engines are described by their working cycle, the number of strokes per cycle, and their method of ignition.

Standby engines must be kept in a state of readiness. To do this, auxiliaries such as starting, fuel delivery, and cooling systems must be prepared and maintained in a state of readiness.

When engines are running, key conditions, such as coolant temperature and exhaust smoke, must be monitored to ensure the engine is running correctly.

This introductory chapter provided the basis for further study of internal combustion engines at higher classes of Power Engineering.

Unit Summary

This is the conclusion of the Prime Movers and Engines unit. The following topics were outlined, discussed and illustrated:

- Construction and operation of a simple steam engine and a simple type of multi-stage steam turbine.
- Differentiate between heat engine and prime mover.
- Explain how heat is converted to mechanical energy to produce work.
- Identify the components of a steam or gas turbine, a cooling tower, and an internal combustion engine.
- Describe the safe, efficient, and proper startup and operation of prime movers and engines, including their lubrication and cooling systems.

Emphasis was placed on how to perform system checks, startup, operation, maintenance, and troubleshooting of prime movers, engines, and their auxiliaries. Power Engineers must be aware of the ramifications of improper startup and operation, and the equipment damage it could lead to.

A self-assessment tool is available on MyPower LMS. Login using the unique user ID and password found on the inside front cover of Unit 1.

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UNIT B-7

Knowledge Exercises and Unit Glossary

Knowledge Exercises – Chapter 1

Name: ______________________ Date: ______________________

Instructor: ______________________ Course: ______________________

Objective 1

1. Describe the differences between Heat Engines and Prime Movers.

2. List at least two applications of the steam engine that are still in use today.

Objective 2

3. Describe the routine inspection of an operating steam engine.

Chapter 1 (Cont.)

4. Describe how to correctly start a steam engine.

Knowledge Exercises – Chapter 2

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. Name the two basic types of steam turbines and explain the difference in how they operate.

2. List and describe the major components of a steam turbine.

Chapter 2 (Cont.)

3. Sketch and describe a simple steam power plant, showing:
   - Boiler
   - Turbine and generator
   - Condenser
   - Condensate pump
   - Boiler feed water heater
   - Boiler feed water pump

Objective 2

4. Explain how labyrinth glands prevent steam leakage along a turbine's shaft.

Chapter 2 (Cont.)

5. Make a single-line diagram of a turbine lubrication system and describe its operation.

Objective 3

6. Explain how flyweights are used to govern the speed of a steam turbine.

Chapter 2 (Cont.)

7. State the purpose of a turbine overspeed trip and explain how it works.

Objective 4

8. Summarize the steps in starting up and shutting down a typical steam turbine driven feedwater pump.

Knowledge Exercises – Chapter 3

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. In a steam power plant, what is the primary purpose of a condenser?

2. What are the two main types of condensers?

3. Why is a surface condenser a better option than the jet condenser?

Objective 2

4. Name the two classes of cooling tower.

5. Name six basic cooling tower components.

Chapter 3 (Cont.)

6. Explain the principle of operation involved in the transfer of heat in a cooling tower.

7. What factors determine the amount of make-up water fed to a cooling tower?

Objective 3

8. Explain how chimney cooling towers work.

Chapter 3 (Cont.)

Objective 4

9. What are the differences in construction and operation between forced and induced draft cooling towers?

Chapter 3 (Cont.)

Objective 5

10. Discuss the methods to avoid freezing a cooling tower during cold weather.

Objective 6

11. What is drift, and why is it undesirable?

Chapter 3 (Cont.)

12. What are the causes of drift?

Knowledge Exercises – Chapter 4

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. Outline the operating principles of a simple gas turbine.

2. State the difference in construction between an aeroderivative gas turbine and a heavy-duty gas turbine. Cite some applications of these two gas turbines in industry.

Chapter 4 (Cont.)

Objective 2

3. Discuss the advantages and disadvantages of gas turbines, as compared to other prime movers.

Objective 3

4. What is the purpose of a regenerator? Explain how it affects the fuel consumption of a gas turbine.

Chapter 4 (Cont.)

5. A combined cycle plant uses both a steam boiler and a gas turbine. Briefly describe how this combination can produce superheated steam using a heat recovery steam generator (HRSG).

Objective 4

6. List the steps for starting a typical automatic gas turbine.

Chapter 4 (Cont.)

7. Identify conditions that an operator should be aware of before starting a gas turbine and its auxiliaries.

Knowledge Exercises – Chapter 5

Name: ______________________ Date: ______________________

Instructor: ______________________ Course: ______________________

Objective 1

1. List the fuels most commonly used by internal combustion engines.

2. What does "governing" mean with respect to internal combustion engines?

3. Describe how gasoline and diesel engines are governed. What is the difference between the two methods?

Objective 2

4. How are two-stroke and four-stroke spark ignition engines lubricated?

Chapter 5 (Cont.)

5. Explain why a two-stroke cycle spark ignition engine does not develop double the power of a four-stroke cycle spark ignition engine.

6. Describe the working cycle of a four-stroke spark ignition engine.

Objective 3

7. Describe the working cycle of a four-stroke compression ignition engine.

Chapter 5 (Cont.)

Objective 4

8. What closes the exhaust and intake valves?

9. List the main engine components attached to a four-stroke engine cylinder head. What is the main difference between the diesel and gasoline engine components?

Objective 5

10. Explain how large stationary diesel engines are started.

Chapter 5 (Cont.)

11. Sketch a closed system diesel engine cooling system. Include the following:
    a) Heat exchanger
    b) Lubricating oil cooler
    c) Expansion tank
    d) Jacket pump and external water pump
    e) Pressure gauges and thermometers

12. Describe the operation of the cooling system drawn in Question 11.

Unit B-7 Glossary

Term	Definition
Aeroderivative	A design, concept, or machine that originates in the aerospace industry.
Bottom dead centre	In a reciprocating machine, the point in travel of a piston or plunger that results in the greatest cylinder volume.
Bucket	A type of turbine blade, common in impulse turbines, which is used to absorb the momentum of the steam or to change the direction of steam flow.
Camshaft	A rotating rod, asymmetrical along its axis, with protruding lobes that convert rotating motion to reciprocating motion. Camshafts are often employed to operate spring-loaded poppet valves.
Carburetor	In a gasoline engine, a device that mixes fuel and air in varying quantities, and at a constant fuel-to-air ratio.
Closed cooling system	With respect to internal combustion engines, a method of cooling an engine with fluid that rejects heat via heat exchange to a secondary coolant.
Compression ratio	The ratio of the volume of a cylinder with its piston at bottom dead centre, to the volume of a cylinder with its piston at top dead centre.
Compression stroke	In an internal combustion engine, the movement of a piston from its bottom dead centre to its top dead centre position, during which air, or an air-fuel mixture, is compressed prior to ignition.
Condenser	A heat exchanger that causes a vapour to change to a liquid by removing latent heat.
Connecting rod	A rod connecting a piston and a crankshaft in a prime mover, pump, or compressor.
Cooling tower	A device that rejects waste heat from water by evaporating a portion of the water, thus cooling the remainder for reuse as industrial coolant.
Counter-flow	When two fluids flow in opposite directions to each other. This may occur in a heat exchanger or a cooling tower.
Crank pin	The part of a crankshaft to which the connecting rod is attached.
Crank web	The part of a crankshaft between the crank pin and the shaft, or between adjacent crankpins.
Crankcase	The part of a machine that encloses a crankshaft.
Crankshaft	A mechanical device used to convert reciprocating motion to rotary motion, or vice-versa.
Crossflow	When two fluids flow at 90 degrees to each other. This may occur in a heat exchanger or a cooling tower.
Crosshead	A flat block between a piston rod and a connecting rod. It eliminates lateral force on the piston. It is found in some reciprocating engines, pumps, and compressors.
Cylinder head	In a reciprocating machine, the fixed enclosure at one end of a cylinder.
Diesel engine	A reciprocating internal combustion engine that operates on a constant pressure cycle, uses compression ignition, and burns light fuel oil.
Distributor	In multiple cylinder gasoline engines, a device that triggers ignition at the beginning of each cylinder's respective power stroke.
Double acting pump	Pump where liquid is discharged when the piston moves in either direction.
Drift	When entrained water particles leave a cooling tower with the flow of air.

Term	Definition
Drift eliminators	An arrangement of barriers within a cooling tower that removes water mist from the air before the air exits to the atmosphere.
Duplex pump	A two-cylinder double-acting reciprocating pump driven directly by the action of two steam cylinders.
Eccentric	"Eccentric" means "located off-centre." An eccentric is a mechanism that converts rotary motion into reciprocating motion by virtue of having its rotational centre located at a distance from the rotational centre of the device to which it is attached.
Eccentric rod	A rod attached to an eccentric, used to transmit motion to a reciprocating part.
Exhaust stroke	In an internal combustion engine, the movement of a piston from its bottom dead centre to its top dead centre position, during which combustion products are expelled from the engine.
External combustion engine	A heat engine where a working fluid, contained internally, is heated by combustion from an external source, such as through a heat exchanger.
Flyweight	A weight that is part of a governor system. It re positions itself based on the shaft rotational speed, due to centrifugal force.
Flywheel	A device that alternately stores and releases kinetic energy.
Four-stroke cycle engine	An engine that requires two crankshaft revolutions to complete one working cycle.
Fuel injector	A nozzle designed to atomize and direct gasoline or oil, under high pressure, into an internal combustion engine.
Fuel oil	Homogeneous hydrocarbon mixtures, in liquid form, used in combustion processes to provide heat.
Garter spring	A small spring that surrounds a machine part, such as a carbon packing ring, to hold the part together.
Gas engine	A reciprocating internal combustion engine that operates on the constant volume cycle, uses spark ignition, and burns gasoline.
Gas turbine	A rotary, constant-flow prime mover and heat engine. It operates on a constant pressure Brayton cycle and consists of a compressor, a combustor, and a turbine.
Gland	A machinery component used to seal a rotating or reciprocating shaft against fluid leakage.
Governing	In prime movers, the automatic control of an engine output with respect to load.
Governor	A mechanism affixed to a prime mover to control its power output in proportion to its load.
Heat engine	A machine, or assembly of machinery, that converts heat energy to mechanical energy through a series of repetitive thermodynamic operations, such as combustion, compression, expansion, boiling, condensation, and cooling.
Heat of compression	The heat energy which results from the conversion of mechanical work done on a confined gas.
Heat recovery steam generator (HRSG)	A boiler that generates steam from heat produced by a chemical process, a thermal process, or a prime mover.
Heat sink	A relatively cold body capable of absorbing large quantities of heat.
Hot well	A reservoir at the base of a steam condenser in which condensate accumulates.

Term	Definition
HRSG	See *heat recovery steam generator (HRSG)*.
Hydraulic relay	A hydraulic device that uses a relatively small signal to apply larger hydraulic force, such as that required to position a valve.
ICE	See *internal combustion engine (ICE)*.
Impulse	In mechanics, the force required to change a body's momentum.
Impulse turbine	A turbine that uses impulse action to change heat energy in the steam to mechanical energy.
Inertia governor	In a steam engine, a governor system that senses the inertia of moving masses attached to a rotating flywheel, thereby using engine speed to infer engine load.
Intake stroke	In an internal combustion engine, the movement of a piston from its top dead centre to its bottom dead centre position, during which air, or an air-fuel mixture, is drawn into the engine.
Internal combustion engine (ICE)	A heat engine where the combustion of a fuel occurs in a chamber that is an integral part of the working fluid's flow circuit.
Jet condenser	A condenser that operates by direct contact of steam with cooling water.
Labyrinth gland	A type of mechanical seal that provides a tortuous path to help prevent leakage.
Momentum	In mechanics, the product of a mass times its velocity.
Monel metal	A nickel-bearing alloy with high tensile strength and resistance to corrosion.
Open cooling system	With respect to internal combustion engines, a method of cooling an engine using fluid that rejects heat by contacting the atmosphere or an open reservoir.
Open cycle gas turbine	A gas turbine where the air used to drive the turbine is drawn from the atmosphere, and then returned to the atmosphere after use.
Overspeed bolt	See *trip pin*.
Overspeed trip	Device installed on turbines as a means of protection from the danger of rotating at excessive speeds.
Pilot valve	A type of hydraulic relay, commonly used on prime mover governing systems.
Piston	A solid cylindrical part that can be positioned within a cylinder to alter its volume.
Piston ring	A ring of spring steel that seals the clearance space between a piston and a cylinder wall, to prevent leakage.
Piston rod	A rod that connects a piston to a crosshead, and transmits force to or from the piston.
Poppet valve	A spring-loaded valve, which operates in a linear direction. Commonly used as intake or exhaust valves for internal combustion engines.
Power stroke	In an internal combustion engine, the movement of a piston from its top dead centre to its bottom dead centre position, when propelled by expanding combustion gases. The engine produces power during this stroke.
Prime mover	A machine that converts a naturally occurring source of energy into mechanical energy.
Rankine cycle	The working cycle that describes the operation of a heat engine comprised of a boiler, a boiler feed pump, a turbine, and a condenser.

Term	Definition
Reaction turbine	A type of turbine that uses the reaction principle to convert heat energy into mechanical energy.
Regenerator, gas turbine	A heat exchanger that recovers heat from exhaust fluids.
Rotor	Rotating or turning part of a mechanism.
Scavenging	The removal of combustion products from an internal combustion engine.
Sheave	A wheel with a grooved rim that transmits force to an attached cable, belt, or rod.
Simple gas turbine	A rotary, constant-flow prime mover and heat engine. It operates on a constant pressure Brayton cycle and consists of a compressor, a combustor, and a turbine.
Single shaft gas turbine	A gas turbine arrangement in which the compressor and the gas turbine are coupled to one shaft.
Slide valve	A valve that admits steam to, and permits the exhaust of steam from, a steam engine.
Speeder	A handwheel for manually adjusting the setpoint speed of a prime mover.
Steam chest	The pressurized chamber from which steam is distributed to the cylinder of a steam engine or the nozzles of a steam turbine.
Steam turbine	A prime mover with a rotary element designed to convert the heat energy of pressurized steam to mechanical energy.
Stroke	In a reciprocating machine, the distance a piston or plunger travels from its top dead centre position to its bottom dead centre position.
Surface condenser	A condenser with a heat transfer surface between a gas to be condensed and a cooling medium (such as water or air).
Throttle valve	A device that controls the flow of working fluid, and adjusts the output energy of a prime mover.
Top dead centre	In a reciprocating machine, the point in travel of a piston or plunger that results in the least cylinder volume.
Trip pin	A heavy spring-loaded pin retained within a rotating shaft, which extends on an overspeed condition, triggering equipment shutdown. Also known as an overspeed bolt.
Two-stroke cycle engine	An engine that requires one crankshaft revolution to complete one working cycle.
Valve rod (steam engine)	In a steam engine, a rod that is attached to a slide valve at one end and the eccentric that drives the valve at the other end.

Additional Workspace

Additional Workspace

Additional Workspace

Additional Workspace

Additional Workspace

Additional Workspace