

●●● **POWER ENGINEERING**

Second Class Part A1

Code Calculations and Legislation

Edition 2.5



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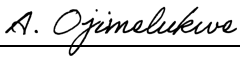
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PanGlobal
Partner in Education

**1-1339 40 Ave NE
Calgary, Alberta
T2E 8N6**

Second Class

Part A1

Code Calculations and Legislation

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CHAPTER 1

ASME Code Calculations: Cylindrical Components

LEARNING OUTCOME

When you complete this chapter you should be able to:

Apply the appropriate formulae from ASME Sections I and VIII to calculations involving cylindrical components, openings, and compensations in boilers and pressure vessels.

LEARNING OBJECTIVES

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

- 1. Calculate the minimum required thickness or the maximum allowable working pressure of ferrous tubing, up to and including 125 mm O.D.*
- 2. Using ASME Sections I and VIII, calculate the required minimum thickness or the maximum allowable working pressure of ferrous piping, drums, and headers.*
- 3. Calculate the required thickness or maximum allowable working pressure of a seamless, unstayed dished head.*
- 4. Calculate the minimum required thickness or maximum allowable working pressure of unstayed flat heads and welded covers.*
- 5. Determine whether or not reinforcement is required for openings in a cylindrical shell, header, or head.*
- 6. Using the ligament efficiency method, calculate the minimum required thickness of a cylindrical drum with two or more openings in the pressure boundary.*

NOTE: The formulas, calculations, and code references found in this chapter are from the 2015 ASME BPVC, which is reproduced in part in the PanGlobal 2018 ASME Academic Extract Volumes 1 and 2.



CHAPTER INTRODUCTION

Second and first class power engineers require detailed, working knowledge of engineering codes and standards. They are often involved with facility upgrades and modifications to pressure piping or equipment. They work with teams for equipment design, upgrade commissioning, operation, or repair. The chief power engineer, in particular, will lead teams and provide guidance and approval for various projects. All of these activities require code compliance.

In the early 1900s, the ASME (American Society of Mechanical Engineers) appointed various committees to formulate standards for the construction of boilers and pressure vessels, including standards for welding, plus guidelines for the care and operation of in-service boilers. These standards and guidelines have been updated over the years in keeping with advancements in materials and technology.

One important component of the standards for pressure vessels is the use of a **safety factor**. The ultimate tensile strength of a material is divided by a defined safety factor to derive the maximum allowable stress for the material. This provides an allowance for any limitations in the testing technology, unusual stress concentrations, non-uniformity of the material, and material flaws. Technological improvements, especially in materials testing and chemistry, have allowed a gradual reduction of the safety factor over the years the ASME BPVC has been in effect.

Consult the ASME BPVC Sections I and VIII Division 1 while studying this chapter. Paragraphs and Figures referenced with a Code section prefix (such as “Figure UG 34”) can be found in the ASME BPVC or the PanGlobal 2018 ASME Academic Extract Volumes 1 and 2.

Note: Unless indicated otherwise, pressures calculated or stated in this chapter refer to gauge pressure.

Note: Materials and formulas used in this chapter are based on the 2015 edition of the ASME BPVC. Most sections can be found in the PanGlobal 2018 ASME Academic Extract Volumes 1 and 2.

Note: Correct measurement units are essential for accurate calculations; students must be well versed in the appropriate units. However, due to the complexity of Code calculations, units may be omitted here until the final answer is derived.

ASME SECTION I - POWER BOILERS

The Preamble of ASME BPVC I includes the following information:

This Code covers rules for construction of power boilers, electric boilers, miniature boilers, high-temperature water boilers, heat recovery steam generators, solar receiver steam generators, and certain fired pressure vessels to be used in stationary service and includes those power boilers used in locomotive, portable, and traction service.

The scope of jurisdiction of Section I applies to the boiler proper and the boiler external piping. Superheaters, economizers, and other pressure parts connected directly to the boiler, without intervening valves, are considered parts of the boiler proper and their construction shall conform to Section I rules.

Materials

Paragraph **PG-6** states that steel plates for any part of a boiler subject to pressure, whether or not exposed to the fire or products of combustion, shall be in accordance with specifications listed in Paragraph **PG-6.1**.

Paragraph **PG-9** states that pipes, tubes, and pressure containing parts in boilers shall conform to one of the specifications listed in Paragraph **PG-9.1**.

Paragraph **PG-16.3** states that the minimum thickness of any boiler plate under pressure shall be 6 mm except for electric boilers constructed under the rules of Part PEB. The minimum thickness of plates to which stays may be attached (in other than cylindrical outer shell plates) shall be 8 mm. When pipe larger than NPS 5 (DN125) is used in lieu of plate for the shell of cylindrical components under pressure, its minimum wall thickness shall be 6 mm.

Paragraph **PG-16.4** states that plate material not more than 0.3 mm thinner than the required thickness calculated by Code formula may be used provided the material specification permits such plate to be furnished not more than 0.3 mm thinner than ordered. (Material specifications are found in ASME Section II Part A.)

Paragraph **PG-16.5** states that pipe or tube material shall not be ordered thinner than the required thickness calculated by using the formulas in Section I. Also, the ordered thickness shall include provision for the allowed manufacturing undertolerance (specified in ASME BPVC II-A) for that particular pipe or tube material.

Design

Paragraph **PG-21** states that whenever the term **maximum allowable working pressure (MAWP)** is used in Section I it refers to gauge pressure.

Paragraph PG-27: Cylindrical Components Under Internal Pressure

The formulas in this part of the code are used to determine the minimum required thickness or the maximum allowable working pressure of piping, tubes, drums, shells, and headers, for operating temperatures equal to or less than those given for the various materials listed in Section II, Part D, and in accordance with the appropriate dimensional categories in PG-27.2.1, PG-27.2.2, and PG-27.2.3.

These formulas are presented in forms transposed for either maximum allowable working pressure, or for minimum thickness.

The symbols used in the formulas are found in Paragraph **PG-27.3** and are defined as follows:

- C = minimum allowance for threading and structural stability (mm) (see **PG-27.4.3**)
- D = outside diameter of cylinder (mm)
- E = efficiency (see **PG-27.4.1**)
- e = thickness factor for expanded tube ends (mm) (see **PG-27.4.4**)
- P = maximum allowable working pressure (MPa) (see **PG-21**)
- R = inside radius of cylinder (mm) (for pipe, the inside radius is determined by the nominal outside radius minus the nominal wall thickness)
- S = maximum allowable stress value at the design temperature of the metal as listed in tables specified in PG-23.1 (see **PG-27.4.2**)
- t = minimum required thickness (mm) (see **PG-27.4.7** for pipe thickness)
- y = temperature coefficient (see **PG-27.4.6**)
- w = weld joint strength reduction factor, per **PG-26**

Additional symbols are listed for stress values and material thicknesses, for bimetallic tube designs.



ASME SECTION VIII, DIVISION 1 - PRESSURE VESSELS

Foreword

The Boiler and Pressure Vessel Committee established rules for new construction of pressure vessels that ensure safe and reliable performance. The Code is not a handbook and cannot replace education, experience, and the use of good engineering judgement. Section VIII-1 applies to small compressed-air receivers sold commercially to the general public as well as to very large pressure vessels used by the petrochemical industry. The Code contains mandatory requirements, specific prohibitions, and non-mandatory guidance for pressure vessel construction.

Materials

Paragraph UG-4 states that materials subject to stress due to pressure shall conform to one of the specifications given in **ASME BPVC II-D**, except as otherwise permitted in Paragraphs **UG-9**, **UG-10**, **UG-11**, **UG-15**, **Part UCS**, **Part UIG**, and the **Mandatory Appendices**.

Paragraph **UG-23(a)** has a table that lists the permissible material compositions, and tables where the material allowable stresses are found (such as **ASME Section II-D** for carbon and low alloy steels, and **Table UCD-23** for ductile iron).

Paragraph **UG-23(d)** prohibits the use of materials other than those allowed by the rules of ASME BPVC VIII-1.

Design

With a few exceptions, ASME Section I requires all longitudinal and circumferential butt joints to be fully examined by volumetric examination (either radiography or ultrasound). However, ASME VIII-1 permits varying degrees of weld joint examination.

Table UW-12, lists the degree of examination for various categories of weld joints. The weld joint efficiency used in the design formulas depends on whether full, spot, or zero radiographic examination is performed after construction. For example, a fully radiographed longitudinal butt-welded joint in a cylindrical shell has a joint efficiency (E) of 1.0. A non-radiographed longitudinal butt-welded joint of the same weld category may have a joint efficiency of 0.7, which corresponds to an increase of about 43% in the required material thickness. The designer must specify the level of radiographic examination to be conducted post-construction, and use the correct joint efficiency during the design phase.

Paragraph UG-20: Design Temperature

With pressure vessels, the maximum temperature used in the design is important, as is the minimum temperature.

The maximum temperature used in design shall be not less than the mean metal temperature (through the thickness) expected under operating conditions.

The minimum temperature used in design shall be the lowest temperature that the vessel will experience from any factor, including normal operation, upset conditions, or environmental conditions. The **Minimum Design Metal Temperature (MDMT)** must be marked on the vessel nameplate, and shall have a corresponding MAWP.

Paragraph UG-27: Thickness of shells under internal pressure

The formulas in this section are used to determine the minimum required thickness of shells when the maximum allowable working pressure is known. These formulas are presented in forms transposed for either maximum allowable working pressure, or for minimum thickness.

The symbols used in the formulas are found in Paragraph **UG-27(b)** and are defined as follows:

- t = minimum required thickness (mm), or actual thickness if calculating P
- P = internal design pressure (MPa) (see **UG-21**)
- R = inside radius of shell course under consideration (mm)
- S = maximum allowable stress value (see **UG-23** and the stress limitations specified in **UG-24**)
- E = joint efficiency for, or the efficiency of, appropriate joint in cylindrical or spherical shells, or the efficiency of ligaments between openings, whichever is less (use **UW-12** for welded vessels, and use **UG-53** for ligaments between openings)



OBJECTIVE 1

Calculate the minimum required thickness or the maximum allowable working pressure of ferrous tubing, up to and including 125 mm O.D.

ASME SECTION I

The following formulas are found in ASME Section I, Paragraph **PG-27.2.1**.

For minimum required thickness:

$$t = \frac{PD}{2S_w + P} + 0.005D + e \quad (1.1)$$

For MAWP:

$$P = S_w \left[\frac{2t - 0.01D - 2e}{D - (t - 0.005D - e)} \right] \quad (1.2)$$

PG-27.2.1 directs users to refer to **PG-27.4.2**, **PG-27.4.4**, **PG-27.4.8**, and **PG-27.4.9** for detailed notes on using these formulas.

Example 1: Boiler Tube

Calculate the minimum required wall thickness of a watertube boiler tube 70 mm O.D. that is strength welded into place in a boiler. Tube is located in the furnace area of the boiler and has an average wall temperature of 350°C. Maximum allowable working pressure is 4000 kPa gauge. Tube material is carbon steel SA-192.

Note: First, check **PG-9** to see if the material is permissible for boiler construction. **PG-9** also indicates whether the material is carbon or alloy steel, which may help in determining the value for y .

Solution 1

For the minimum thickness of tubing up to and including 125 mm O.D., use equation 1.1 (**PG-27.2.1**).

$$t = \frac{PD}{2S_w + P} + 0.005D + e$$

Where:

$$P = 4 \text{ MPag}$$

$$D = 70 \text{ mm}$$

$$e = 0 \text{ (strength welded. See PG-27.4.4.)}$$

$$S = 87.8 \text{ MPa (from ASME II-D Table 1A, SA-192 at 350°C)}$$

$$w = 1.0, \text{ since the operating temperature is below 400°C and carbon steel tubes are exempt from the requirements of PG-26 and Table PG-26 (see Note 3, Table PG-26)}$$

Solving:

$$\begin{aligned} t &= \frac{4 \times 70}{(2 \times 1.0 \times 87.8) + 4} + 0.005(70) + 0 \\ &= \frac{280}{179.6} + 0.35 \\ &= 1.56 + 0.35 \\ &= \mathbf{1.9 \text{ mm (Ans.)}} \end{aligned}$$

Example 2: Superheater Tube

Calculate the maximum allowable working pressure, in MPa, for a 75 mm O.D. and 4.75 mm minimum thickness superheater tube connected to a header by strength welding. The average tube temperature is 400°C. The tube material is SA-213-T11.

Note: Check **PG-9** for boiler tube materials before starting calculations. All non-bolting ferrous materials for Section I and Section VIII-1 use are in Table 1A of Section II-D.

Solution 2

For the MAWP of tubing up to and including 125 mm O.D., use equation 1.2 (**PG-27.2.1**).

$$P = S_w \left[\frac{2t - 0.01D - 2e}{D - (t - 0.005D - e)} \right]$$

Where:

$$t = 4.75 \text{ mm}$$

$$D = 75 \text{ mm}$$

$$e = 0 \text{ (strength welded. See PG-27.4.4)}$$

$$S = 102 \text{ MPa (ASME II-D, Table 1A, SA-213-T11 at 400°C)}$$

$$w = 1.0, \text{ since the operating temperature is below } 427^\circ\text{C (Table PG-26, Cr-Mo steel)}$$

Solving:

$$\begin{aligned} P &= 102 \times 1.0 \times \left[\frac{2 \times 4.75 - 0.01 \times 75 - 2 \times 0}{75 - (4.75 - 0.005 \times 75 - 0)} \right] \\ &= 102 \times \left[\frac{9.5 - 0.75}{75 - (4.75 - 0.375)} \right] \\ &= 102 \times \frac{8.75}{70.625} \\ &= \mathbf{12.64 \text{ MPa or } 12 \text{ 640 kPa (Ans.)}} \end{aligned}$$

Note: The nameplate pressure is in kPa, and not in MPa. This is because **CSA B51 5.1.4** only permits whole numbers when specifying pressure and temperature ratings on nameplates.

The tubes were strength welded in Examples 1 and 2. For calculations involving tubes expanded into place, the appropriate value of e is found in Paragraph **PG-27.4.4**.



OBJECTIVE 2

Using ASME Sections I and VIII, calculate the required minimum thickness or the maximum allowable working pressure of ferrous piping, drums, and headers.

In cylindrical vessels, the stress set up by the pressure on the longitudinal joints is equal to twice the stress on the circumferential joints.

ASME SECTION I

The following formulas are found in ASME Section I, Paragraph **PG-27.2.2**.

The information for piping, drums, or headers may be given with either the inside (R) or outside (D) measurement.

Using the outside diameter:

$$t = \frac{PD}{2SE + 2yP} + C \quad (2.1)$$

$$P = \frac{2SE(t - C)}{D - 2y(t - C)} \quad (2.2)$$

Using the inside radius:

$$t = \frac{PR}{SE - (1 - y)P} + C \quad (2.3)$$

$$P = \frac{SE(t - C)}{R + (1 - y)(t - C)} \quad (2.4)$$

PG-27.2.2 directs users to refer to **PG-27.4.1**, **PG-27.4.3**, and **PG-27.4.5** through **PG-27.4.8** for detailed notes on using these formulas.

Example 3: Steam piping

Calculate the minimum required thickness of seamless piping which carries steam at a pressure of 6200 kPa gauge and a temperature of 375°C. Piping is plain end. Nominal pipe size is DN250 (NPS 10) (273.05 mm OD) and the material is SA-335-P11.

Note: Check **PG-9** for acceptable pipe materials before starting calculations.

Note: Plain-end pipe does not have its wall thickness reduced when joining to another pipe. For example, lengths of pipe welded together, rather than being joined by threading, are classed as plain-end pipes.

Solution 3

Use equation 2.1 (see **PG-27.2.2**).

$$t = \frac{PD}{2SE + 2yP} + C$$

Where:

$$P = 6.2 \text{ MPa}$$

$$D = 273.05 \text{ mm}$$

$$C = 0 \text{ (PG-27.4.3 specifies values of } C \text{ for threaded pipe only)}$$

$$S = 104 \text{ MPa (see ASME II-D, Table 1A, SA-335-P11 at } 375^\circ\text{C)}$$

$$E = 1.0 \text{ (see PG-27.4.1, seamless pipe as per PG-9.1)}$$

$$y = 0.4 \text{ (see PG-27.4.6, ferritic steel less than } 480^\circ\text{C)}$$

Solving:

$$\begin{aligned} t &= \frac{6.2 \times 273.05}{2(104 \times 1.0) + 2(0.4 \times 6.2)} \\ &= \frac{1692.91}{208 + 4.96} \\ &= \frac{1692.91}{212.96} \\ &= 7.95 \text{ mm (Ans.)} \end{aligned}$$



Example 4: Boiler Proper Piping (using outside diameter)

Calculate the maximum allowable working pressure in kPa for a seamless steel pipe of material SA-335-P1. Nominal pipe size is DN300 (NPS 12) Schedule 80 (323.85 mm OD and a wall thickness of 17.48 mm). The operating temperature is 450°C. The pipe is plain ended.

Note: Check **PG-9** for materials before starting calculations.

Note: If the piping dimensions (O.D. and thickness) are not given in a question, refer to the PanGlobal Academic Supplement “Table of Pipe Dimensions.”

Solution 4

Use equation 2.2 (see **PG-27.2.2**).

$$P = \frac{2SE(t - C)}{D - 2y(t - C)}$$

Where:

$$D = 323.85 \text{ mm}$$

$$t = 17.48 \text{ mm}$$

$$C = 0 \text{ (PG-27.4.3 specifies values for } C \text{ for threaded pipe only)}$$

$$S = 101 \text{ MPa (Section II-D, Table 1A, SA-335-P1 at } 450^\circ\text{C)}$$

$$E = 1.0 \text{ (see PG-27.4.1, seamless pipe product form, as per Section II-D, Table 1A, SA-335-P1)}$$

$$y = 0.4 \text{ (see PG-27.4.6, ferritic steel at } 450^\circ\text{C)}$$

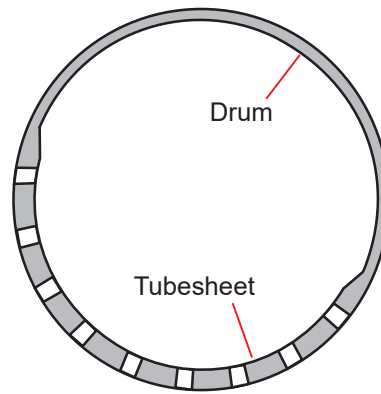
Solving:

$$\begin{aligned} P &= \frac{2(101 \times 1.0) \times (17.48 - 0)}{323.85 - 2 \times 0.4 \times (17.48 - 0)} \\ &= \frac{202 \times 17.48}{323.85 - 13.98} \\ &= \frac{3530.96}{309.87} \\ &= 11.4 \text{ MPa} \\ &= \mathbf{11\,400 \text{ kPa (Ans.)}} \end{aligned}$$

Example 5: Drum (using inside radius)

A welded watertube boiler drum of SA-515-60 material is fabricated to an inside radius of 470 mm on the tubesheet and 490 mm on the drum. There is no corrosion allowance. Plate thickness of the tubesheet and drum are 60 mm and 40 mm respectively. Longitudinal joint efficiency is 100%, the ligament efficiency along the axis of the shell (longitudinally) is 56%, and ligament efficiency transverse to the axis of the shell (circumferentially) is 30%. Operating temperature will not exceed 300°C. Determine the maximum allowable working pressure based on:

- the drum and
- the tubesheet

Figure 1 – Welded Watertube Boiler Drum


Note: This is a common example of a watertube drum fabricated from two plates of different thickness. Greater material thickness is required where the boiler tubes enter the drum than is required for a plain drum. For economy, the drum is designed to meet the pressure requirements for each situation.

Note: Check **PG-6** for materials before starting calculations. The material SA 515-60 is carbon steel plate.

Solution 5

This solution has two parts:

- Drum - consider the drum to be plain with no penetrations (note: this section is also called the 'wrapper sheet' to distinguish it from the whole drum).
- Tubesheet - consider the tubesheet to have penetrations for boiler tubes.

Solution Part (a): Use equation 2.4 (inside radius R) (see **PG-27.2.2**).

$$\text{Drum } P = \frac{SE(t - C)}{R + (1 - y)(t - C)}$$

Where:

S = 115 MPa (from Section II-D Table 1A, SA-515-60 at 300°C)

E = 1 (see **PG-27.4.1**)

t = 40 mm

C = 0 (**PG-27.4.3**, drum design has zero corrosion allowance)

R = 490 mm (for the drum)

y = 0.4 (see **PG-27.4.6**, ferritic steel less than 480°C)

Solving:

$$\begin{aligned} \text{Drum } P &= \frac{(115 \times 1)(40 - 0)}{490 + (1 - 0.4)(40 - 0)} \\ &= \frac{4600}{490 + 24} \\ &= 8.95 \text{ MPa (Ans.)} \end{aligned}$$



Solution Part (b): Use equation 2.4 (inside radius R) (see **PG-27.2.2**).

$$\text{Tubesheet P} = \frac{SE(t - C)}{R + (1 - y)(t - C)}$$

Where:

S = 115 MPa (from Section II-D Table 1A, SA-515-60 at 300°C)

E = 0.56 (refer to **PG-52.3**. The **equivalent longitudinal efficiency** of the circumferential ligaments is the circumferential ligament efficiency multiplied by 2. This is because, in comparison, the shell carries half the stress in the circumferential plane as it does in the longitudinal plane. The lesser of $2 \times 0.3 = 0.6$ and 0.56 is used in the equation)

t = 60 mm

C = 0 (**PG-27.4.3**, drum design has zero corrosion allowance)

R = 470 mm (for the tubesheet)

y = 0.4 (see **PG-27.4.6**, ferritic steel less than 480°C)

Solving:

$$\begin{aligned} \text{Tubesheet P} &= \frac{(115 \times 0.56)(60 - 0)}{470 + (1 - 0.4)(60 - 0)} \\ &= \frac{3864}{470 + 36} \\ &= \mathbf{7.64 \text{ MPa (Ans.)}} \end{aligned}$$

The maximum allowable working pressure is based on the lowest number between the drum (wrapper sheet) and the tubesheet. **Therefore, the MAWP is 7.64 MPa. (Ans.)**

ASME SECTION VIII

In Section VIII-1, the formulas that are used to calculate minimum required thickness and maximum allowable working pressure of pipes, drums, and cylindrical headers are contained in **UG-27**. Section VIII does NOT distinguish between tubes and pipes (as Section I does in **PG-27.2**).

Paragraph **UG-31** invokes the rules of **UG-27** for tubes and pipe when used as tubes or shells, even though **U-1(c)(2)(i)** says that vessels having an inside diameter, width, height, or cross-sectional diameter not exceeding 152 mm are exempt from the Code. Hence, heat exchanger tubes and other similar components would have to be calculated as cylinders.

The formulas in **UG-27** and Mandatory Appendix 1 apply to all materials in cylindrical shells.

Thin Cylindrical Shells under Internal Pressure

- (1) Circumferential stress (at longitudinal joints). Paragraph **UG-27(c)(1)** states “When the thickness does not exceed one-half of the inside radius, or P does not exceed $0.385SE$, the following formulas shall apply:”

Therefore, when $t \leq 0.5R$ or $P \leq 0.385SE$, use:

$$t = \frac{PR}{(SE - 0.6P)} \quad (2.5)$$

or

$$P = \frac{SEt}{R + 0.6t} \quad (2.6)$$

- (2) Longitudinal stress (at circumferential joints). Paragraph **UG-27(c)(2)** states: “When the thickness does not exceed one-half of the inside radius, or P does not exceed $1.25SE$, the following formulas shall apply:”

Therefore, when $t \leq 0.5 R$ or $P \leq 1.25SE$, use:

$$t = \frac{PR}{2SE + 0.4P} \quad (2.7)$$

or

$$P = \frac{2SEt}{R - 0.4t} \quad (2.8)$$

Alternative formulas are listed in **Mandatory Appendix 1, Supplementary Design Formulas, Paragraph 1-1**. They are based on outside radius, instead of inside radius, and may be used instead of those given in **UG-27(c)** and **UG-27(d)**.

Thick Cylindrical Shells under Internal Pressure

As internal pressures increase above 20 MPa, special considerations must be given to the construction of the vessel as specified in **Paragraph U-1(d)**. When t exceeds $0.5R$, a more accurate equation is required to determine the thickness. The formulas for thick walled cylinders are listed in **Mandatory Appendix 1, Supplementary Design Formulas, Paragraph 1-2**.

For circumferential stress (at longitudinal joints), when $t > 0.5R$ or $P > 0.385SE$, the following formulas shall be used. (where R = inside radius and R_o = outside radius)

To determine t when the MAWP is known:

$$t = R \left(\exp \left[\frac{P}{SE} \right] - 1 \right) = R_o \left(1 - \exp \left[\frac{-P}{SE} \right] \right)$$

Because $\exp \left[\frac{P}{SE} \right]$ is the same as $e^{\frac{P}{SE}}$, the equation may be written as

$$t = R \left(e^{\frac{P}{SE}} - 1 \right) = R_o \left(1 - e^{\frac{-P}{SE}} \right) \quad (2.9)$$

Note that the value of ‘ e ’ in this case is 2.7182, which is the base of natural logs. Remember that the natural log of any number, ‘ x ’, may be denoted as either **ln x** or **log _{e} x** .



To determine the MAWP when t is known:

$$P = SE \log_e \left(\frac{R+t}{R} \right) = SE \log_e \left(\frac{R_o}{R_o-t} \right) \quad (2.10)$$

These formulas may be used in lieu of those given in **UG-27(c)**.

For longitudinal stress (at circumferential joints), when $t > 0.5R$ or $P > 1.25SE$, the following formulas shall be used:

To determine t when the MAWP is known:

$$t = R \left(Z^{\frac{1}{2}} - 1 \right) = R_o \left(\frac{Z^{\frac{1}{2}} - 1}{Z^{\frac{1}{2}}} \right) \quad (2.11)$$

To determine the MAWP when t is known:

$$P = SE (Z - 1) \quad (2.12)$$

Where:

$$Z = \left(\frac{R+t}{R} \right)^2 = \left(\frac{R_o}{R} \right)^2 = \left(\frac{R_o}{R_o-t} \right)^2 \quad (2.13)$$

Note: Formulas 2.9 to 2.13 are for internal pressure only.

Example 6: Thin Shell

A vertical pressure vessel is constructed of SA-515-60 material in accordance with Section VIII-1. Design pressure is 690 kPa and temperature is 230°C. The actual finished inside diameter is designated at 2440 mm. The corrosion allowance is 3 mm. The joint efficiency is 0.85.

If the allowable stress is 118 MPa, find:

- the required shell thickness and;
- the outside radius.

Solution 6

The calculation: $0.385SE = 38.62$ MPa. Since the design pressure of 0.690 MPa ≤ 38.62 MPa, use equation 2.5 (see Section VIII-1, **UG-27**).

Note: Calculate the required thickness based on the inside radius at the fully corroded condition, which is $1220 + 3 = 1223$ mm. When this method is used, the corrosion allowance is considered to be added to the inside of the vessel. Therefore, when the vessel is in its un-corroded state, the inside radius will be 1220 mm.

$$\begin{aligned} \text{a)} \quad t &= \frac{PR}{SE - 0.6P} + \text{corrosion allowance} \\ &= \frac{0.69 \times 1223}{118 \times 0.85 - 0.6 \times 0.69} + 3 \\ &= \frac{843.87}{99.886} + 3 \\ &= 8.45 + 3 \\ &= \mathbf{11.45 \text{ mm (Ans.)}} \end{aligned}$$

$$\text{b)} \quad \text{The outside radius will be } 1220 \text{ mm} + 11.45 \text{ mm} = \mathbf{1231.45 \text{ mm (Ans.)}}$$

Example 7: For thick shell

Calculate the required shell thickness, the inside radius, and the outside radius of an exchanger shell, operating at 500°C, with $P = 21$ MPa, $R = 17$ cm (before adding corrosion allowance), $S = 26.5$ MPa, and $E = 1.0$. The design requires a corrosion allowance of 3 mm.

Solution 7

First, determine which equation to use. The design pressure of 21 MPa exceeds the calculation $0.385SE$ (which equals 10.2 MPa). However, 21 MPa does NOT exceed the calculation $1.25SE$ (which equals 33.1 MPa). Therefore, use equation 2.9.

$$\begin{aligned} t &= R \left(e^{\frac{P}{SE}} - 1 \right) \\ &= 170 \left(2.7182^{\frac{21}{26.5}} - 1 \right) \\ &= 170 (2.7182^{0.79} - 1) \\ &= 170 (2.208 - 1) \\ &= 205.5 \text{ mm} \end{aligned}$$

The total thickness, including corrosion allowance:

$$\begin{aligned} t &= 205.5 + 3 \\ &= \mathbf{208.5 \text{ mm (Ans.)}} \end{aligned}$$

The outside radius will be $170 \text{ mm} + 208.5 \text{ mm} = \mathbf{378.49 \text{ mm (Ans.)}$



OBJECTIVE 3

Calculate the required thickness or maximum allowable working pressure of a seamless, unstayed dished head.

ASME SECTION I: DISHED HEAD CALCULATIONS

The paragraphs from **PG-29** must be considered when performing calculations on dished heads.

PG-29.1 states that the thickness of a blank, unstayed dished head with the pressure on the concave side, when dished to a segment of a sphere, shall be calculated by the following formula:

$$t = \frac{5PL}{4.8Sw} \quad (3.1)$$

Where:

t = minimum required thickness of head (mm) (excluding corrosion or other allowances)

P = maximum allowable working pressure (MPa)

L = radius (mm) to which the head is dished, measured on the concave side

S = maximum allowable working stress (MPa) (from ASME II-D, Table 1A)

w = weld joint strength reduction factor per **PG-26**

Paragraph **PG-29.2** states: “The radius to which the head is dished shall be not greater than the outside diameter of the flanged portion of the head. Where two radii are used, the longer shall be taken as the value of L in the formula.” If the dish radius L was to exceed the diameter D, the resulting head would be excessively shallow, resulting in more bending stress than Formula 3.1 (see **PG-29.1**) considers.

Heads covered by **PG-29.1** and **PG-29.2** are typically referred to as torispherical or flanged-and-dished heads. The central portion of the head is spherically dished and the knuckle of the head (i.e. the transition from the dished portion to the cylindrical flange) is a portion of a torus. The knuckle radius is small compared to the dish radius; therefore, the dish radius is used for the dimension “L”.

Example 8: Flanged-and-dished head

Calculate the thickness of a seamless, blank unstayed dished head having pressure on the concave side. The head has a diameter of 1085 mm and is a segment of a sphere with a dish radius of 918 mm. The maximum allowable working pressure is 2500 kPa and the material is SA-285-A. The metal temperature does not exceed 250°C. Determine if this thickness meets ASME Section I.

Solution 8

Use equation 3.1 (see Paragraph **PG-29.1** for blank unstayed dished heads formed to a segment of a sphere).

$$t = \frac{5PL}{4.8Sw}$$

Where:

$$P = 2.5 \text{ MPa}$$

$$L = 918 \text{ mm}$$

$$S = 88.9 \text{ MPa (from ASME II-D, Table 1A, SA-285-A at 250°C)}$$

$$w = 1.0, \text{ since the temperature is below the } 427^\circ\text{C minimum in Table PG-26}$$

Solving:

$$\begin{aligned} t &= \frac{5(2.5 \times 918)}{4.8 \times 88.9 \times 1.0} \\ &= \mathbf{26.89 \text{ mm (Ans.)}} \end{aligned}$$

PG-29.6 states “No head, except a full-hemispherical head, shall be of a lesser thickness than that required for a seamless shell of the same diameter.” Therefore, to determine if this head thickness meets Code, the thickness of the shell must be calculated.

Use equation 2.1 (see Paragraph **PG-27.2.2**).

$$t = \frac{PD}{2SE + 2yP} + C$$

Where:

$$D = 1085 \text{ mm}$$

$$y = 0.4 \text{ (see PG-27.4, note 6, ferritic steel less than } 480^\circ\text{C)}$$

$$E = 1 \text{ (welded)}$$

Solving:

$$\begin{aligned} t &= \frac{2.5 \times 1085}{2(88.9 \times 1) + 2(0.4 \times 2.5)} \\ &= \frac{2712.5}{177.8 + 2} \\ &= 15.086 \text{ mm} \end{aligned}$$

Because the calculated head thickness (26.89 mm) is equal to or exceeds the thickness of a seamless shell of the same diameter, the calculated head thickness meets Code requirements.

Note: It would be a rare head for which the thickness given by Equation 3.1 would be less than that for a seamless shell of the same diameter and allowable stress. For most ASME “flanged and dished” heads, $L = D$, so the shell would be about half as thick as the head.



Paragraph **PG-44** specifies that boilers have suitable openings, such as manholes, handholes, inspection openings, and washout openings. Elliptical manholes shall not be less than 300×400 mm in size. Circular manholes shall not be less than 380 mm in diameter. Handholes shall not be less than $70 \text{ mm} \times 89 \text{ mm}$. There are no specific dimensions for other inspection or washout openings.

Note: **CSA-B51 6.3.5** requires elliptical manholes to be at least 305×406 mm, and circular manholes to be at least 406 mm inside diameter.

Often, dished heads require manhole openings. The head requires compensation for the material removed, in order to retain its strength. To address this, paragraph **PG-29.3** states:

When a head, dished to a segment of a sphere, has a flanged-in manhole or access opening that exceeds 150 mm in any dimension, the thickness shall be increased by not less than 15% of the required thickness for a blank head computed by the above formula, but in no case less than 3 mm additional thickness over a blank head. Where such a dished head has a flanged opening supported by an attached flue, an increase in thickness over that for a blank head is not required. If more than one manhole is inserted in a head, the thickness of which is calculated by this rule, the minimum distance between the openings shall be not less than one-fourth of the outside diameter of the head.

Note: The thickness compensation applies to flanged-in manholes that do not have the additional support of an attached flue. A manhole with both flange and flue is exempt from material compensation.

Example 9: Flanged-and-dished head with flanged-in manhole

Calculate the thickness of a seamless, unstayed dished head with pressure on the concave side, having a flanged-in manhole, 305×406 mm. The head has an outside diameter of 1206.5 mm and is dished to a segment of a sphere, with a dish radius of 1143 mm. The maximum allowable working pressure is 1550 kPa. The material is SA-285-C. The metal temperature does not exceed 220°C .

Solution 9

Paragraph **PG-29.5** is used to determine the minimum thickness of any form of head with a flanged-in manhole opening.

First, **PG-29.5** directs the designer to check if the radius of the dish L is at least 80% of the diameter of the outside diameter of the head (typically, the same as the O.D. of the shell D).

$$\frac{\text{dish radius}}{\text{shell diameter}} = \frac{1143}{1206.5} = 0.9474$$

Since 0.9474 is greater than 0.8, the dimension of L will be 1143 mm. If, say, the ratio was 0.785, the value used in the calculation would be 0.8 L .

Use equation 3.1 (see Paragraph **PG-29.1**).

$$t = \frac{5 PL}{4.8Sw}$$

Where:

$$P = 1.55 \text{ MPa}$$

$$L = 1143 \text{ mm}$$

$$S = 108 \text{ MPa (from ASME II-D Table 1A, SA-285-C at } 220^\circ\text{C)}$$

$$w = 1.0, \text{ since the temperature is below } 427^\circ\text{C in Table PG-26}$$

$$\begin{aligned} t &= \frac{5(1.55 \times 1143)}{4.8 \times 108 \times 1.0} \\ &= 17.088 \text{ mm} \end{aligned}$$

This thickness is for a blank head. **PG-29.3** requires this thickness to be increased by 15% or 3 mm, whichever is greater.

Therefore:

$$17.088 \times 0.15 = 2.56 \text{ mm}$$

This is less than 3 mm, so the thickness must be increased by 3 mm.

Therefore:

$$\begin{aligned} \text{Required head thickness} &= 17.088 + 3.0 \\ &= \mathbf{20.088 \text{ mm (Ans.)}} \end{aligned}$$

Semi-ellipsoidal head

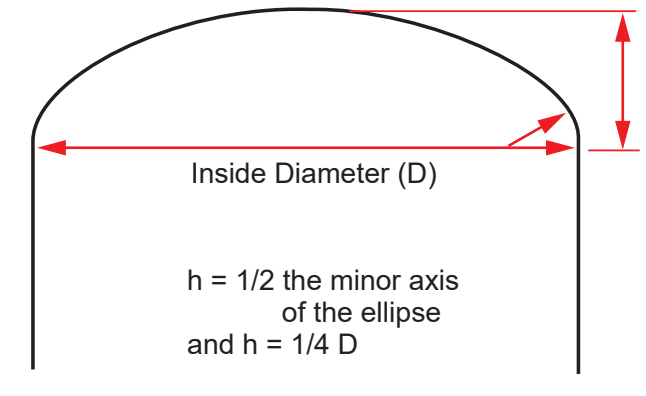
A semi-ellipsoidal head is of a form in which half the minor axis (the depth of the head) is at least equal to one-quarter of the inside diameter of the head. According to paragraph **PG-29.7**, a blank head of a semi-ellipsoidal form shall be made at least as thick as the required thickness of a seamless shell of the same diameter as determined in Paragraph **PG-27** (see **PG-27.2.2**), or in **Non-Mandatory Appendix A, Paragraph A-317**. If a flanged in manhole that meets the Code requirements is placed in an ellipsoidal head, the thickness of the head shall be the same as for a head dished to a segment of a sphere (see **PG-29.1** and **PG-29.5**) with a dish radius equal to eight-tenths the diameter of the shell and with the added thickness for the manhole as specified in **PG-29.3**.

Thus, Paragraph **PG-29.7** combines several rules:

1. seamless shell rule **PG-27.2.2**
2. dished head rule **PG-29.1**
3. flanged-in manhole rule **PG-29.4**

A semi-ellipsoidal head, as described in **PG-29.7**, is shown in Figure 2.

Figure 2 – Semi-Ellipsoidal Head





Full-hemispherical head

Paragraphs **PG-29.11** and **PG-29.6** apply to full-hemispherical heads. **PG-29.6** states that unlike semi-ellipsoidal, torispherical, and flat heads, full hemispherical heads may be of a lesser thickness than that required for a seamless shell of the same diameter. This is because hemispherical heads do not carry bending stress. Rather, the material carries only membrane stress, and is therefore very efficient in its method of carrying stress.

The thickness of a blank, unstayed, full-hemispherical head with the pressure on the concave side shall be calculated according to Paragraph **PG-29.11**:

$$t = \frac{PL}{2S_w - 0.2 P} \quad (3.2)$$

Where:

t = minimum thickness of head (mm)

P = maximum allowable working pressure (MPa)

L = radius to which the head was formed (mm) (measured on the concave side of the head)

S = maximum allowable working stress (MPa) (from ASME II-D, Subpart 1, Table 1A)

w = weld joint strength reduction factor per **PG-26**

The above formula shall not be used when the required thickness of the head given by the formula exceeds 35.6% of the inside radius. Instead, the following formula must be used:

$$t = L \left(Y^{\frac{1}{3}} - 1 \right) \quad \text{where:} \quad Y = \frac{2(S_w + P)}{2S_w - P} \quad (3.3)$$

For example, a hemispherical head that is 1000 mm ID would have to be greater than 178 mm thick by formula 3.2 in order for formula 3.3 to apply. That is a very thick head and would rarely be encountered.

Example 10: Full-hemispherical head

Calculate the minimum required thickness in mm for a blank, unstayed, full-hemispherical head with the pressure on the concave side. Radius to which the head is dished is 190.5 mm. Maximum allowable working pressure is 6205 kPa, and the head material is SA-285-C. Average temperature of the header is 300°C.

Solution 10

Use equation 3.2 (see **PG-29.11**).

$$t = \frac{PL}{2S_w - 0.2P}$$

Where:

$$P = 6.205 \text{ MPa}$$

$$L = 190.5 \text{ mm}$$

$$S = 107 \text{ MPa (from ASME II-D Table 1A, SA-285-C at 300°C)}$$

$$w = 1.0, \text{ since the temperature is below the } 427^\circ\text{C minimum in Table PG-26}$$

Solving:

$$\begin{aligned} t &= \frac{6.205 \times 190.5}{2 \times 107 \times 1.0 - 0.2(6.205)} \\ &= \frac{1182.05}{214 - 1.241} \\ &= \frac{1182.05}{212.759} \\ &= 5.56 \text{ mm (Ans.)} \end{aligned}$$

To ensure the correct equation has been used, check to see if the calculated thickness exceeds 35.6% of the inside radius:

$$190.5 \text{ mm} \times 0.356 = 67.8 \text{ mm}$$

5.56 mm is less than 67.8 mm. Therefore, the correct formula from **PG-29.11** was used. **PG-16.3** states that the minimum thickness of any boiler plate under pressure shall be 6 mm. The calculated thickness from **PG-29.11** is 5.56 mm. Therefore, the minimum thickness of the hemispherical head shall be **6 mm (Ans.)**

If the full-hemispherical head in Example 11 contained a flanged in manhole, then **PG-29.12** would apply. This paragraph states that if a Code-acceptable flanged-in manhole (see **PG-44**) is placed in a full-hemispherical head, the thickness of the head shall be the same as for a head dished to a segment of a sphere (see **PG-29.1** and **PG-29.5**), with the added thickness for the manhole as specified in **PG-29.3**. The dish radius shall equal eight-tenths the outside diameter of the head.

ASME SECTION VIII-1: DISHED HEAD CALCULATIONS

Sections VIII-1 and VIII-2 each contain rules for the design of spherical shells, heads, and transition sections. There are significant differences in the equations due to the different design approaches used. This chapter uses only Section VIII-1 equations.

Section VIII-1 has rules for head configurations including spherical, hemispherical, ellipsoidal, and torispherical shapes.



Spherical Shells and Hemispherical Heads

Paragraphs **UG-27(d)** provides the formulas for the required thickness of thin, fully spherical shells under internal pressure. Paragraph **UG-32(e)** provides formulas for hemispherical heads under internal pressure. The formulas are identical, except that **UG-27(d)** uses the inside radius R (formulas 3.4 and 3.5 below), whereas **UG-32(e)** substitutes the inside spherical radius L for R . This is because **UG-32(e)** applies to ALL formed heads (ellipsoidal, semi-ellipsoidal, torispherical, and conical), where L is consistently defined as the spherical or crown radius. In these formed heads, the crown radius does not equal the spherical radius; however for hemispherical heads, it does.

$$t = \frac{PR}{2SE - 0.2P} \quad (3.4)$$

or

$$P = \frac{2SEt}{R + 0.2t} \quad (3.5)$$

Where: $t \leq 0.356R$ or $P \leq 0.665SE$

For thick shells, where $t > 0.356R$ or $P > 0.665SE$, **Mandatory Appendix 1, Section 1-3** is used. This section of the code provides the following equations:

When P is known and t is desired:

$$t = R \left(e^{\frac{0.5P}{SE}} - 1 \right) = R_o \left(1 - e^{-\frac{0.5P}{SE}} \right) \quad (3.6)$$

When t is known and P is desired:

$$P = 2.0 SE \ln \left(\frac{R+t}{R} \right) = 2.0 SE \ln \left(\frac{R_o}{R_o-t} \right) \quad (3.7)$$

These formulas may be used in lieu of those in **UG-27(d)**.

Example 11: Hemispherical head

A pressure vessel is built of SA-516-70 material and has an inside diameter of 2440 mm. The internal design pressure is 690 kPa at 232°C. The corrosion allowance is 3 mm. What is the required thickness of its hemispherical heads, if the allowable stress is 138 MPa? The head is constructed with butt welds, having a joint efficiency is 0.85.

Solution 11

The result of $0.665SE = 0.665 \times 138\text{MPa} \times 0.85 = 78\text{ MPa}$. Because this exceeds the design pressure of 690 kPa, use equation 3.4 (see Paragraph **UG-32(e)**).

The inside radius in a corroded condition is equal to:

$$\begin{aligned} R &= 1220 + 3 \text{ (corrosion allowance)} \\ &= 1223 \text{ mm} \\ t &= \frac{PR}{2SE - 0.2P} + \text{corrosion allowance} \\ &= \frac{0.69 \times 1223}{2(138 \times 0.85) - 0.2(0.69)} + 3 \\ &= \frac{843.87}{234.46} + 3 \\ &= 3.6 + 3 \\ &= \mathbf{6.6 \text{ mm (Ans.)}} \end{aligned}$$

The calculated thickness is less than $0.356R$; therefore, equation 3.4 is acceptable.

Example 12: Spherical head

A cylindrical pressure vessel with an internal diameter of 3048 mm has a spherical head with a thickness of 25.4 mm. Determine the maximum allowable working pressure if the allowable stress is 113 MPa. The head is constructed with butt welds, having a joint efficiency is 0.85.

Solution 12

Because no corrosion allowance is stated, the design pressure will act on the given internal diameter. Use equation 3.5 (see Paragraph **UG-32(e)**) since t is less than $0.356R$.

$$\begin{aligned} P &= \frac{2SEt}{R + 0.2t} \\ &= \frac{2(113 \times 0.85 \times 25.4)}{1524 + 0.2(25.4)} \\ &= \frac{4879.34}{1529.08} \\ &= \mathbf{3.191 \text{ MPa (Ans.)}} \end{aligned}$$

The calculated pressure is less than $0.665SE$; therefore, equation 3.5 is acceptable.



Ellipsoidal Heads

The commonly used ellipsoidal head has a ratio of base inside radius to inside depth of 2:1 (see Figure 3(a)). The actual shape can be approximated by a torispherical head, with a spherical radius of $0.9D$ and a knuckle radius of $0.17D$ (see Figure 3(b)). The required thickness of 2:1 heads, with pressure on the concave side, is given in **UG-32(c)**.

$$t = \frac{PD}{2SE - 0.2P} \quad (3.8)$$

or

$$P = \frac{2SEt}{D + 0.2t} \quad (3.9)$$

Where:

t_s = minimum specified thickness of the head after forming, mm.

D = inside base diameter, mm

E = joint efficiency factor

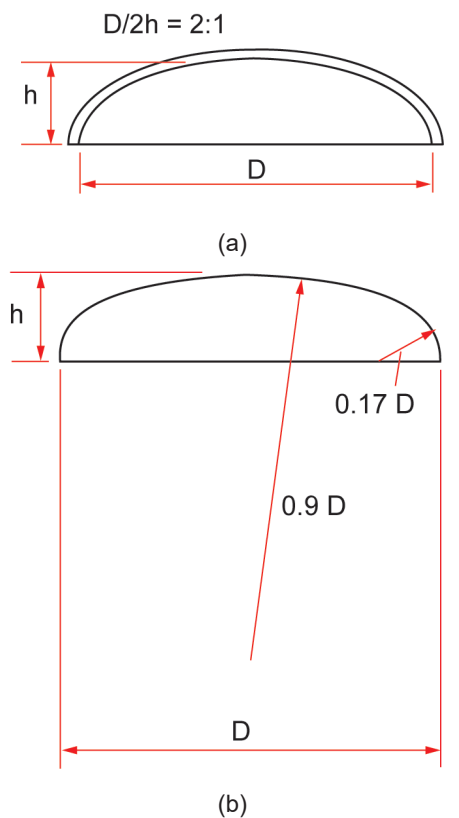
P = pressure on the concave side of the head, MPa

S = allowable stress for the material, MPa

t = thickness of the head, mm

Note: The ratio t_s/L must be greater than or equal to 0.002, where “L” is the crown or spherical radius. Also, t_s must be greater than or equal to t . For ratios of t_s/L less than 0.002, **Mandatory Appendix 1-4(f)** must be met.

Figure 3 – Ellipsoidal Head

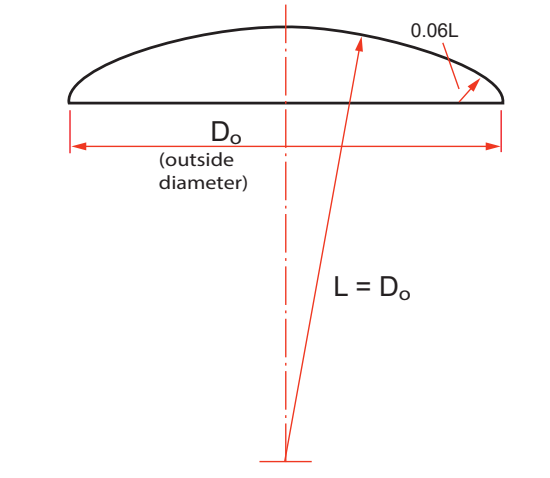


Section VIII-1 does not give any P/S limitations or rules for ellipsoidal heads when the ratio of P/S is large.

Torispherical Heads

Shallow torispherical heads, commonly referred to as flanged and dished heads, can be built according to Paragraph **UG-32(d)**. The most common torispherical heads have a spherical inside crown radius L equal to D_o and a knuckle radius r equal to $0.06L$, as shown in Figure 4.

Figure 4 – Torispherical Head



The required thickness of a flanged and dished head of the above proportions is

$$t = \frac{0.885PL}{SE - 0.1P} \quad (3.10)$$

or

$$P = \frac{SEt}{0.885L + 0.1t} \quad (3.11)$$

Where:

t_s = minimum specified thickness of the head after forming, mm.

E = joint efficiency factor

L = inside spherical radius, mm

P = pressure on the concave side of the head, MPa

S = allowable stress, MPa

t = thickness of the head, mm

Note: The ratio t_s/L must be greater than or equal to 0.002, where “ L ” is the crown or spherical radius. Also, t_s must be greater than or equal to t . For ratios of t_s/L less than 0.002, **Mandatory Appendix 1-4(f)** must be met.

Shallow heads with internal pressure are subjected to a stress reversal at the knuckle. This stress reversal could cause buckling of the shallow head as the ratio D/t increases.



Case Study Comparison, using ASME VIII-1

This case study is included for interest sake, as a comparison of the required minimum thicknesses of various shell/head designs, made of material with the same S value (137 MPa), the same internal diameter (1200 mm), the same design pressure (10 MPa) and the same joint efficiency (100%).

a) Cylindrical shell:

$$t = \frac{PR}{SE - 0.6P} = \frac{10 \times 600}{137 - 0.6(10)} = 45.80 \text{ mm}$$

b) Hemispherical shell: ($L = D/2$)

$$t = \frac{PL}{2SE - 0.2P} = \frac{10 \times 600}{2 \times 137 - 0.2(10)} = 22.06 \text{ mm}$$

c) Semi-elliptical (2:1) head:

$$t = \frac{PD}{2SE - 0.2P} = \frac{10 \times 1200}{2 \times 137 - 0.2(10)} = 44.12 \text{ mm}$$

d) Conical shell (half apex angle $\theta = 30^\circ$):

$$t = \frac{PD}{2(SE - 0.6P) \cos \theta} = \frac{10 \times 1200}{2 \times 131 \times 0.866} = 52.89 \text{ mm}$$

e) Torispherical (dished) head: (note: $L = D + 2t$)

$$t = \frac{0.885PL}{SE - 0.1P} = \frac{0.885 \times 10 \times (1220 + 2t)}{137 - 0.1(10)} = 91.27 \text{ mm}$$

f) Flat head ($C = 0.33$)

$$t = D \sqrt{\frac{CP}{SE}} = 1200 \times \sqrt{\frac{0.33 \times 10}{137}} = 186.24 \text{ mm}$$

OBJECTIVE 4

Calculate the minimum required thickness or maximum allowable working pressure of unstayed flat heads and welded covers.

UNSTAYED FLAT HEADS AND WELDED COVERS

Flat plate is often used for heads and covers in boilers and pressure vessels. A flat plate that is used as an end closure or head of a pressure vessel may be an integral part of the vessel construction (being formed with the cylindrical shell) or it may be a separate component that is welded to the shell. Alternatively, flat plate may be a separate, flat component, attached by bolts or similar mechanism to a flange on the end of the shell. Bolted covers are not within the scope of this Objective.

ASME SECTION I: FLAT HEAD CALCULATIONS

The minimum thickness of unstayed flat heads and cover plates shall conform to the requirements given in **PG-31**. **PG-31.2** defines the notations used in **PG-31** and in **Figure PG-31**, which shows details of the various attachment arrangements. Paragraph **PG-31.3** gives the formulas to calculate the minimum required thickness of flat, unstayed, circular and non-circular heads, covers, and blind flanges.

Circular Cover Plates

When a **circular** cover plate is integral with the shell or attached by welding, the required thickness is governed by the formula in **PG-31.3.2**

$$t = d \sqrt{\frac{CP}{S}} \quad (4.1)$$

Where:

t = minimum required thickness of flat head or cover, mm

d = diameter of the head, measured as indicated in Figure PG-31, in mm

C = a factor that depends on the method of attachment of the head and on the dimensions of the shell, pipe or header. These factors are listed and explained in **PG-31.4**.

P = maximum allowable working pressure, MPa

S = maximum allowable stress value of the material, from ASME II-D Subpart 1, Table 1A (MPa)

Note: The formulas used to determine thickness may be transposed to solve for the maximum allowable working pressure for a flat head or cover when the actual thickness is known.



Non-Circular Cover Plates

Flat, unstayed, non-circular covers are governed by formulas in **PG-31.3.3**. These covers may be square, rectangular, elliptical, obround, or segmental in design. The primary formula differs from the circular formula only by a factor, Z .

$$t = d \sqrt{\frac{Z C P}{S}} \quad (4.2)$$

The secondary formula defines the factor Z , which depends on the ratio between the short and long spans of the cover.

$$Z = 3.4 - \frac{2.4d}{D} \quad (4.3)$$

Where:

d = the length of the short span

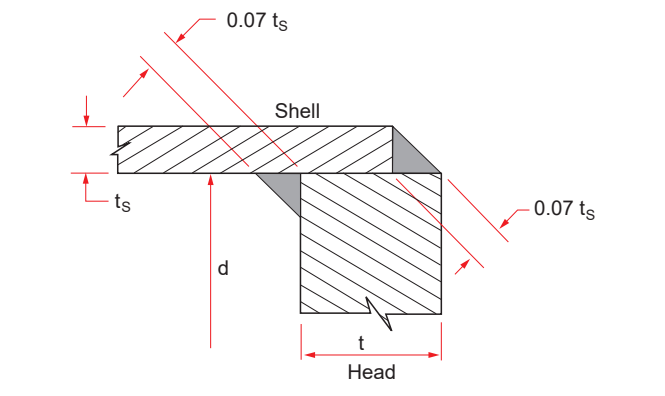
D = the length of the long span, measured perpendicular to the short span

Note: The calculated value of Z need not exceed $2 \frac{1}{2}$.

Example 13: Circular, welded flat head - minimum required thickness

Calculate the minimum required thickness for the circular head shown in Figure 5. The head and shell material are both SA-285-A. The thickness t_s is 19 mm. The maximum allowable working pressure is 2500 kPa at 250°C maximum. The inside diameter of the shell is 762 mm, and $E = 1$. Head joint welding meets Code requirements.

Figure 5 – Circular Flat Head



Solution 13

This design corresponds to that shown in Figure **PG-31(e)**. Code requirements for that figure must be used.

Since this is a **circular** head, we can use equation 4.1.

$$t = d \sqrt{\frac{C P}{S}}$$

Where:

$$P = 2.5 \text{ MPa (given)}$$

$$d = 762 \text{ mm (given)}$$

$$S = 88.9 \text{ MPa (from ASME II-D Table 1A, SA-285-A at 250°C)}$$

$$C = 0.33 \text{ m (see Figure PG-31 sketch (e), Note 1)}$$

To determine the value of 'C', we must first find 'm'. **PG-31.2** provides three necessary definitions:

$$m = \text{the ratio of } t_r/t_s$$

$$t_r = \text{thickness required for pressure of seamless shell, pipe, or header}$$

$$t_s = \text{minimum specified thickness of shell, pipe, or header}$$

The question gives t_s as 19 mm. Equation 2.3 (Paragraph **PG-27.2.2**) must be used to find t_r .

$$t_r = \frac{PR}{SE - (1 - y)P} + C$$

Where:

$$R = d/2 = 381 \text{ mm}$$

$$E = 1 \text{ (see PG-27.4, note 1)}$$

$$y = 0.4 \text{ (see PG-27.4, note 6)}$$

$$C = 0 \text{ (see PG-27.4, note 3)}$$

$$\begin{aligned} t_r &= \frac{2.5 \times 381}{(88.9 \times 1) - (1 - 0.4) \times 2.5} + 0 \\ &= \frac{952.5}{87.4} \\ &= 10.9 \text{ mm} \end{aligned}$$

Next, determine m:

$$\begin{aligned} m &= \frac{t_r}{t_s} \\ &= \frac{10.9}{19} \\ &= 0.574 \end{aligned}$$

After determining m, calculate C:

$$\begin{aligned} C &= 0.33 \times m \\ &= 0.33 \times 0.574 \\ &= 0.19 \end{aligned}$$



PG-31.4 states that the minimum value of C for this design must be 0.20. Since 0.19 is less than 0.20, use $C = 0.20$ in equation 4.1.

$$\begin{aligned}
 t &= d \sqrt{\frac{C P}{S}} \\
 &= 762 \sqrt{\frac{0.20 \times 2.5}{88.9}} \\
 &= 762 \times 0.075 \\
 &= \mathbf{57.15 \text{ mm (Ans.)}}
 \end{aligned}$$

It is interesting to note that the required minimum shell thickness is 10.9 mm, yet the required minimum thickness of the flat blank head is approximately 5.2 times greater, at 57.15 mm.

Example 14: MAWP of circular flat head

Calculate the maximum allowable working pressure for a circular flat head, designed as shown in **Figure PG-31(d)**. The shell and head are both 30.5 mm thick. The material is SA-285-B. The head joint weld meets Code requirements. The shell inside diameter is 600 mm. Operating temperature will not exceed 300°C.

Solution 14

$$t = 30.5 \text{ mm}$$

$$S = 96.6 \text{ MPa (from ASME II-D, Table 1A, SA-285-B at 300°C)}$$

$$d = 600 \text{ mm}$$

$$C = 0.13 \text{ (from Figure PG-31(d))}$$

Use equation 4.1 (**PG-31.3.2.**), transposed to find 'P'.

$$\begin{aligned}
 t &= d \sqrt{\frac{C P}{S}} \\
 P &= \frac{S t^2}{C d^2} \\
 &= \frac{96.6 \times (30.5)^2}{0.13 \times (600)^2} \\
 &= \mathbf{1.92 \text{ MPa (Ans.)}}
 \end{aligned}$$

ASME SECTION VIII-1: FLAT HEAD CALCULATIONS

ASME Section VIII vessels are covered by similar equations for the design of welded and integral (not bolted), unstayed heads. Circular heads are governed by **UG-34(c)(2)** in which the minimum required thickness is given by:

$$t = d \sqrt{\frac{C P}{S E}} \quad (4.5)$$

UG-34 (c)(3) gives the formula for non-circular welded and integral (not bolted) flat unstayed heads.

$$t = d \sqrt{\frac{Z C P}{S E}} \quad (4.6)$$

$$Z = 3.4 - \frac{2.4d}{D} \quad \text{Where: } Z \leq 2.5 \quad (4.7)$$

d = diameter, or short span, measured as indicated in **Figure UG-34** (mm)

C = dimensionless factor (between 0.1 and 0.33) depending on the method of attachment of head, shell dimensions, and other items listed in **UG-34(d)**

P = internal design pressure, MPa

S = maximum allowable stress value, MPa

E = joint efficiency (from **Table UW-12**) of any **Category A** weld, as defined in **UW-3(a)**

t = minimum required thickness of flat head or cover, mm

Z = a dimensionless factor of non-circular heads and covers that depends on the ratio of short span to long span

Note: In ASME VIII-1, UG-34, E refers only to Category A welds. In the case of flat heads, Category A welds are those used to construct the flat head proper. Attachment welds between flat heads and the main shell are Category C welds. In other words, E does not refer to the efficiency of the head-to-shell joint.

The value of E depends on the degree of non-destructive examination performed.



Example 15: Integral flat plate

Using the rules of Paragraph **UG-34**, determine the minimum required thickness of an integral, flat, unstayed circular head with an internal pressure, $P = 17$ MPa, an allowable stress, $S = 120$ MPa, and a head diameter, $d = 610$ mm in its un-corroded state. There are no butt weld joints within the head (the head is made of a single piece). There is a corrosion allowance of 4 mm. The corner detail conforms to **Figure UG-34(b-2)** (assume that $m = 1$).

Solution 15

Use equation 4.5 (see **Figure UG-34(b-2)**).

Where:

$$C = 0.33(m) = 0.33(1) = 0.33$$

$$d = 610 + 4 \times 2 = 618 \text{ mm (fully corroded state)}$$

$$P = 17 \text{ MPa}$$

$$S = 120 \text{ MPa}$$

$$E = 1$$

$$\begin{aligned} t &= d \sqrt{\frac{CP}{SE}} + \text{corrosion allowance} \\ &= 618 \times \sqrt{\frac{0.33 \times 17}{120 \times 1}} + 4 \\ &= 137.6 \text{ mm (Ans.)} \end{aligned}$$

OBJECTIVE 5

Determine whether or not reinforcement is required for openings in a cylindrical shell, header, or head.

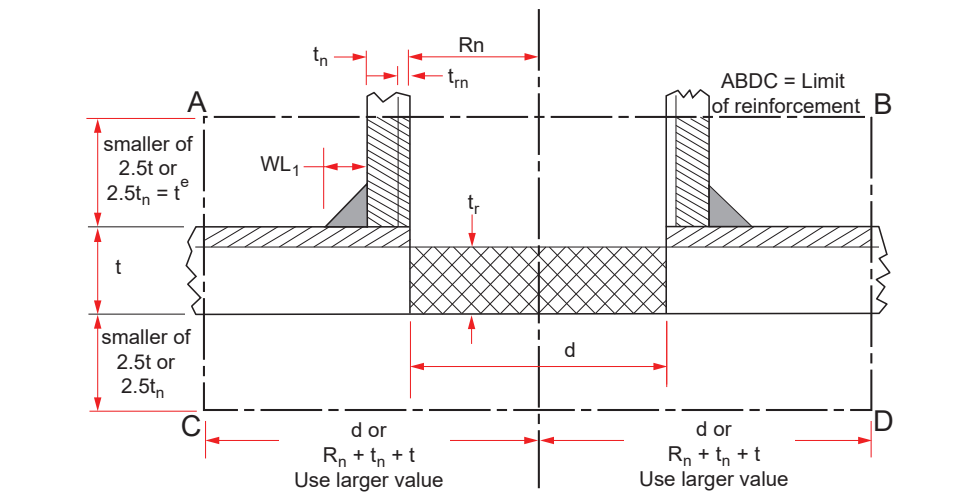
Openings through the pressure boundary of a vessel require extra design consideration to keep loading and stresses at acceptable levels. An examination of the pressure boundary may indicate that extra material is needed near the opening to keep stresses at acceptable levels. This extra material may be provided by increasing the wall thickness of the shell or nozzle or by adding a reinforcement plate around the opening. The rules in the ASME BPVC that deal with reinforced openings are known interchangeably as **reinforcement rules** or **compensation rules**.

The stress analysis basis used in the ASME Codes to analyze nozzle reinforcement is called *Beams on Elastic Foundation* (Hetenyi, 1946). Although the methods used are a simplified application of the **elastic foundation theory**, experience has shown that they are acceptable.

ASME Codes Section I and Section VIII-1 give two methods for examining the acceptability of openings in the pressure boundary for pressure loads only. The first method, called the **reinforced opening** or **area replacement** method is used when nearby substitute areas replace the area removed by the opening. The second method is the ligament efficiency method. This method determines the effectiveness of the material between adjacent openings to carry the stress compared with the area of metal that was there before the openings existed. Curves have been developed to simplify this examination. For single openings, only the area replacement method is used. For multiple openings, either method may be used.

Since stress is related to load and cross-sectional area, areas are substituted when making calculations. The location of the replacement area is very important. Equations have been developed to describe the limits in which reinforcement can be located. Reinforcement limits are found parallel and perpendicular to the shell surface from the opening. These are shown in Figure 6. Similar figures are found in both ASME Section I and ASME Section VIII-1.

Figure 6 – Reinforcement Limits



When an opening is cut into a vessel wall for the attachment of a nozzle with diameter d (as in Figure 6), the vessel wall thickness t is usually greater than the minimum required thickness t_r . The area $t_r \times d$ represents the required material removed to form the opening. This is the area that must be compensated for.



The “**Limits of Metal Available for Compensation**” are shown by box ABCD in Figure 6 above. All reinforcing material must lie within these dimensions. The rules for determining these limits are found in **ASME Section I, Paragraph PG-36**, and in **ASME Section VIII-1, Paragraph UG-40**.

If the sum of the excess material found within the limits of reinforcement equals or exceeds the area of the required material removed ($t_r \times d$), then the hole is adequately reinforced. If the hole is not adequately reinforced, then additional compensating material may be added within the limits of reinforcement, by:

- Increasing the size of the attachment welds
- Extending the nozzle through the shell
- Increasing the thickness of the shell, nozzle, or both, over the minimum required by code
- Providing a reinforcement pad of sufficient thickness within the limits of reinforcement.

ASME SECTION I

ASME Section I, Paragraph **PG-32** “Openings in Shells, Headers and Dished Heads” contains rules for maintaining the integrity of a vessel’s pressure boundary when openings are made. Paragraph **PG-32.1** states that Paragraphs **PG-32** through **PG-39** shall apply to all openings (except for flanged-in manholes as stated in Paragraph **PG-29**). **PG-32.1.2** deals with tube holes in a definite pattern that may be designed according to Paragraph **PG-52**. **PG-32.1.3**, and **PG-32.1.4** provide the rules for inherently compensated openings. These openings do not require extensive reinforcement calculations, because the vessels or vessel components are sufficiently strong without the addition of compensating material.

To determine if an opening is inherently compensated, certain preliminary calculations are necessary. **PG-32.1.4** states that no calculation is necessary to determine the availability of compensation for a single opening in shells or headers when the diameter of the finished opening, d , does not exceed the larger of (a) or (b) below:

(a) $d_{\max}$ calculated for single openings, as follows

$$d_{\max} = 8.08 [Dt(1 - K)]^{1/3} \quad (\text{for SI units only}) \quad (5.1)$$

Where:

D = the outside diameter of the shell, header, or dished head containing the opening, mm

t = the nominal thickness of the head, shell, or header, mm

K = $PD/1.82St$ (where K shall not exceed 0.990) (See **PG-32.1.1**)

(b) the smaller of $\frac{1}{4}$ the inside diameter of the shell or header, or 60 mm

Example 16: Reinforcement of nozzle abutting vessel

Determine if reinforcement is required for a 100 mm I.D. nozzle, located in a cylindrical boiler shell. The nozzle abuts the vessel wall and is attached by a full-penetration weld. The O.D. of the shell is 1000 mm. The thickness of the shell wall is 25.4 mm. The thickness of the nozzle wall is 10 mm. Shell material is SA-515-60 and the nozzle material is SA-106-B. The maximum allowable working pressure is 4500 kPa, and the design temperature is not to exceed 200°C. All joint efficiencies $E = 1$.

Solution 16

Since this is a boiler shell, ASME Section I rules apply (see **PG-32.1.4**).

To use equation 5.1, first calculate the value of K .

$$K = \frac{PD}{1.82St}$$

Where:

$$P = 4.5 \text{ MPa}$$

$$D = 1000 \text{ mm}$$

$$S = 118 \text{ MPa}$$

$$t = 25.4 \text{ mm}$$

$$\begin{aligned} K &= \frac{PD}{1.82St} \\ &= \frac{4.5 \times 1000}{1.82(118 \times 25.4)} \\ &= 0.825 \end{aligned}$$

Knowing K , determine the value of “(a)”, which is $d_{\max}$:

$$\begin{aligned} d_{\max} &= 8.08[Dt(1 - K)]^{1/3} \\ &= 8.08 \times [1000 \times 25.4 \times (1 - 0.825)]^{1/3} \\ &= 8.08 \times (25\,400 \times 0.175)^{1/3} \\ &= 8.08 \times (4445)^{1/3} \\ &= 8.08 \times 16.44 \\ &= 132.85 \text{ mm} \end{aligned}$$

Next, determine $\frac{1}{4}$ of the inside diameter of the shell:

$$0.25 \times (1000 - 25.4 \times 2) = 237.3 \text{ mm}$$

Take the smaller of 60 mm and 237.3 mm, which is 60 mm. This is the value of “(b)”.

ASME BPVC I **PG-32.1.4 Openings in Shells and Headers** states “No calculation need be made to determine the availability of compensation for a single opening... in shells or headers when the diameter of the finished opening, d , does not exceed the larger of (a) or (b).” In this example, “(a)” equals 132.85 mm, and “(b)” equals 60 mm. The ID of the nozzle opening is 100 mm, which despite being larger than “(b)”, does not exceed “(a)”. **Therefore the opening is inherently compensated, and reinforcement is not required. (Ans).**



Note: The previous calculation only determines whether a shell opening is inherently compensated. If the opening is not, compensation calculations are necessary to show whether the shell, nozzle, and nozzle attachments, as designed, provide sufficient excess material within the limits of compensation, or whether additional reinforcement is necessary. This is beyond the scope of Second Class Power Engineering.

ASME SECTION VIII, DIVISION 1

Section VIII-1, Paragraph **UG-36(c)(3)** states that when vessels are not designed to experience rapid pressure fluctuations while in service, openings in their shells do not require reinforcement other than that inherent in their construction, as long as the conditions of **UG-36(c)(3)(-a)** through **UG-36(c)(3)(-d)** are met. These include certain dimensional requirements related to:

- whether the required minimum shell thickness is greater than, equal to, or less than 10 mm
- whether the shell connection is threaded, studded, or expanded.

If the criteria of **UG-36(c)(3)** are not met, the reinforcement calculations in Paragraph **UG-37** must be performed, and compensation provided if necessary.

Example 17: Reinforcement of nozzle abutting vessel

Determine if reinforcement is required for a 60 mm I.D. nozzle located in a cylindrical pressure vessel shell. The vessel is not designed for service with rapidly fluctuating pressure, and has no corrosion allowance. The nozzle abuts the vessel wall and is attached by a full-penetration weld. The O.D. of the shell is 1000 mm. The thickness of the shell wall is 25.4 mm, and the thickness of the nozzle wall is 10 mm. The shell material is SA-516-60 and the nozzle is SA-106-B. The maximum allowable working pressure is 4500 kPa. The design temperature is 200°C. All joint efficiencies $E = 1.0$.

Solution 17

Since this is a pressure vessel shell, the rules of ASME Section VIII-I Paragraph **UG-36(c)(3)** apply.

UG-36(c)(3)(-a) states that reinforcement is not required if welded, brazed, and flued connections meet all applicable design and construction rules, and have a finished opening not larger than:

- 89 mm diameter – in vessel shells or heads with a required minimum thickness of 10 mm or less;
- 60 mm diameter – in vessel shells or heads with a required minimum thickness over 10 mm.

In this example, the required shell thickness is 25.4 mm (there is no corrosion allowance). **The nozzle diameter is 60 mm. Because this meets the second criterion, no reinforcement is required. (Ans.)**

Note: Paragraph **UG-36(c)(1)** states that metal added as corrosion allowance shall not be considered as reinforcement.

OBJECTIVE 6

Using the ligament efficiency method, calculate the minimum required thickness of a cylindrical drum with two or more openings in the pressure boundary.

INTRODUCTION

The tubesheet of a firetube boiler is a flat head, located at either end of a shell, with regular openings for tube attachment. For a watertube boiler, the tubesheet is the part of a boiler mud drum, steam drum, or header, with regular openings for tube attachment. Compensation for single openings is determined by the method in the previous chapter. Multiple openings, such as those in a tubesheet, are covered by the ligament rules in ASME Section I, Paragraph **PG-52** and ASME Section VIII-1, Paragraph **UG-53**.

Ligament rules consider only the strength of material between the shell openings; they do not consider the attached tubes as providing compensating material. The ligament efficiency, determined by following ASME BPVC rules, is used in the determination of the minimum required thickness, or the maximum allowable working pressure, of cylindrical components under internal pressure (see ASME Section I Paragraph **PG-27**, and ASME Section VIII-1 Paragraph **UG-27**).

LIGAMENTS

A ligament is an area of metal between adjacent holes of a tubesheet. In a watertube boiler drum, there are three types of ligaments to consider:

1. **Longitudinal:** located between adjacent holes along the length of the drum.
2. **Circumferential:** located between adjacent holes around the circumference of the drum.
3. **Diagonal:** located between adjacent holes on a line that is diagonal (ie. at an angle) to the longitudinal and circumferential directions.

The rules of ligaments are applicable to groups of openings that form a definite pattern. These rules also apply to openings not spaced to exceed two diameters centre to centre.

The following symbols are used in the formulas in ASME Section I Paragraph **PG-52**, when calculating ligament efficiency:

p = longitudinal pitch of adjacent openings (mm)

p' = diagonal pitch of adjacent openings (mm)

P_1 = pitch between corresponding openings in a series of symmetrical groups of openings (mm)

p_c = circumferential pitch of adjacent openings, in. (mm)

d = diameter of openings (mm)

n = number of openings in length p_1

E = ligament efficiency

ASME Section I Figures **PG-52-2**, **PG-52.3**, **PG-52.4**, and **PG-52.5** show various patterns of holes in tubesheets. The same diagrams appear in ASME Section VIII-1, Figures **UG-53.1**, **UG-53.2**, **UG-53.3**, and **UG-53.4**. These are similar to Figures 7 through 10 in this chapter.



When the pitch of the tubes on every row is equal (Figure 7), use the formula:

$$E = \frac{p - d}{p} \quad (6.1)$$

Note: Figure 7 is similar to ASME I **Figure PG-52.2** and ASME VIII-1 **Figure UG-53.1**.

When the pitch of the tubes on any row is unequal (Figures 8 and 9), use the formula:

$$E = \frac{p_1 - nd}{p_1} \quad (6.2)$$

Note: Figure 8 and 9 are similar to ASME I **Figures PG-52.2** and **PG-52.3** respectively, and ASME VIII-1 **Figures UG-53.1** and **UG-53.2** respectively.

For ligament efficiency of holes drilled along a diagonal (Figure 10):

- For Section I boilers, follow Paragraph **PG-52.4**, and refer to **Figures PG-52.1** and **PG-52.5**
- For Section VIII-1 pressure vessels, follow Paragraphs **UG-53(c)**, **UG-53(d)**, and **UG-53(e)**, and refer to **Figures UG-53.1** through **Figure UG-53.6**.

Note: Figure 10 is similar to ASME I **Figure PG-52.5** and ASME VIII-1 **Figure UG-53.4**.

Figure 7 – Example of tube spacing with hole pitch equal in every row

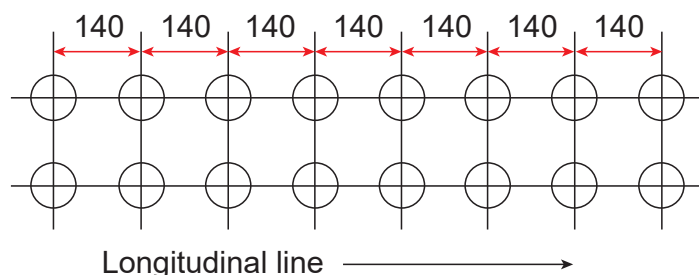


Figure 8 – Example of tube spacing with hole pitch unequal in every second row

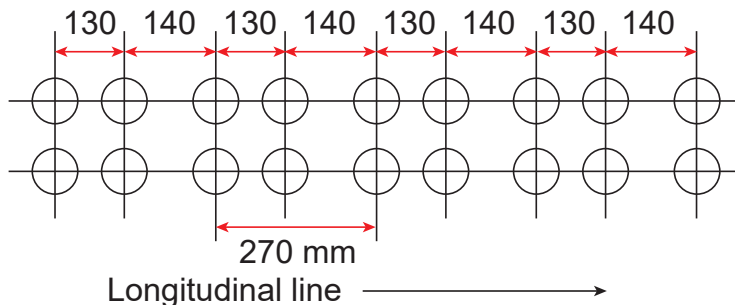


Figure 9 – Example of tube spacing with hole pitch varying in every second and third row

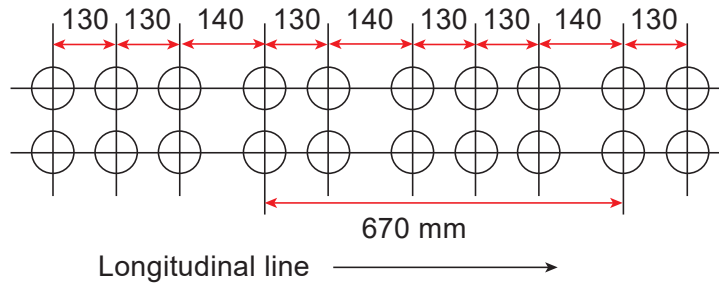
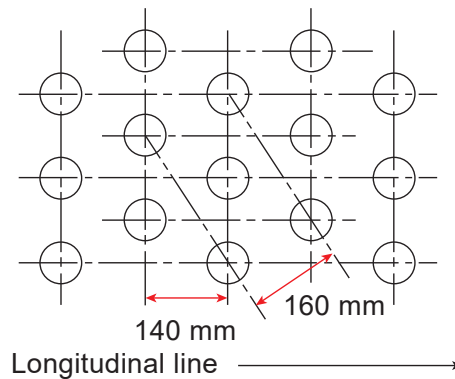


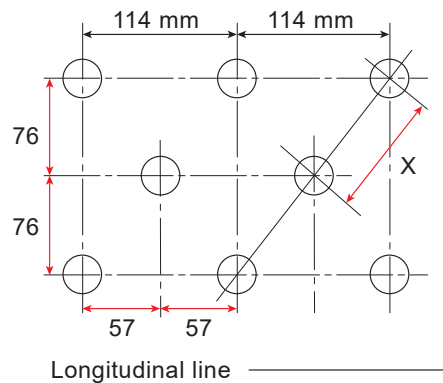
Figure 10 – Example of tube spacing with tube holes on diagonal lines



Example 18: Thickness of cylindrical drum with tube holes

Using the rules of Section I, determine the minimum thickness of a 920 mm I.D. cylindrical drum that has a series of openings in the pattern shown in Figure 11. The openings are 63.5 mm diameter on a staggered pattern of three longitudinal rows with 76 mm circumferential spacing and 116 mm longitudinal spacing. Maximum allowable working pressure is 4100 kPa at a temperature of 250°C. The drum material is SA-516-55, and the tube material is SA-209-T1. Openings are not located in or near any butt-welded joint.

Figure 11 – Tube hole spacing for Example 18





Solution 18

Using Figure PG-52.1, the diagonal pitch p' must be found.

$$\begin{aligned}\text{Diagonal pitch, } p' \text{ ("X" in Figure 11)} &= \sqrt{58^2 + 76^2} \\ &= \sqrt{3364 + 5776} \\ &= \sqrt{9140} = 95.6 \text{ mm}\end{aligned}$$

Using equation 6.1:

$$\begin{aligned}E &= \frac{p - d}{p} \\ &= \frac{116 - 63.5}{116} \\ &= 0.4526\end{aligned}$$

Determine the ratio p'/p :

$$\begin{aligned}\frac{p'}{p} &= \frac{95.6}{116} \\ &= 0.824\end{aligned}$$

Refer to ASME I **Figure PG-52.1**. The upper solid line marks the line of equal efficiency between longitudinal and diagonal ligaments. Below this line, the diagonal ligament is weaker. On **Figure PG-52.1** locate 0.824 on the sloped lines and follow this up to the point where it intersects the vertical 45.26% line of longitudinal efficiency. Follow a horizontal line to the y-axis, and read the equivalent longitudinal efficiency of the diagonal ligaments. This is approximately 38%.

Because the equivalent longitudinal efficiency of the diagonal ligaments (38%) is less than the efficiency of the longitudinal ligaments (45.26%), the diagonal ligament efficiency governs the tube sheet design. Therefore, E used in PG-27.2.2 will be 38%.

Note: Whenever the longitudinal efficiency and the ratio p'/p intersect between the “Curve of condition of equal efficiency of diagonal and longitudinal ligaments” and the “Curve of condition of equal efficiency of diagonal and circumferential ligaments,” the diagonal ligament efficiency governs the tubesheet design.

Using ASME I, Paragraph **PG-27.2.2**, inside radius formula:

$$t = \frac{PR}{SE - (1 - y)P} + C \quad (6.3)$$

$P = 4100 \text{ kPa}$ or 4.1 MPa

$R = 460 \text{ mm}$

$S = 108 \text{ MPa}$ (from ASME II-D, SA-516-55 at 250°C)

$E = 0.38$ (from Figure PG-52.1: diagonal ligament efficiency)

$C = 0$

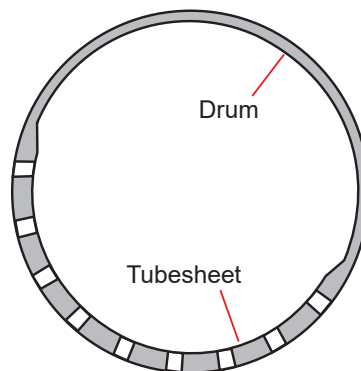
$Y = 0.4$ for ferritic steel below 480°C

$$\begin{aligned} t &= \frac{PR}{SE - (1 - y)P} + C \\ &= \frac{4.1 \times 460}{108 \times 0.38 - (1 - 0.4) \times 4.1} \\ &= \frac{1886}{41.04 - 2.46} \\ &= \frac{1886}{38.58} \\ &= 48.9 \text{ mm (Ans.)} \end{aligned}$$

The minimum required thickness of the drum shell would be 48.9 mm without any allowance for corrosion.

Note: The minimum thickness of this drum without tube holes, having the same outside diameter of the finished tube sheet (see Figure 12 below), would be 19 mm. Therefore, the drum could be manufactured from two half shells; the tubesheet section being 48.9 mm thick, and the drum (wrapper sheet) section being 19 mm thick. The outside diameter of the drum would be 1018.8 mm. Each part of the shell would meet the conditions of **PG-27.2.2**.

Figure 12 – Example: Tube holes in Drum manufactured from two half shells





CHAPTER QUESTIONS

The following questions provide candidates with experience using the ASME Codes.

1. Calculate the minimum required wall thickness of a watertube boiler tube 75 mm O.D. that is strength welded in place in a boiler drum. The tube will be in the furnace area of the boiler and have an average wall temperature of 350°C. Maximum allowable working pressure is 3500 kPa. Tube material is SA-192.
2. Calculate the thickness of a boiler steam header designed with a seamless, unstayed, full hemispherical head, with pressure on the concave side. Inside radius of the header and the radius to which the head is dished is 304 mm; MAWP is 6205 kPa; and the header and head material is SA-204-A. Average temperature of the header is 400°C. Header has a flanged-in circular inspection opening 100 mm diameter. Also, determine whether the head requires compensation.
3. A pressure vessel is constructed from SA-204-A with an inside diameter of 1830 mm. Design pressure is 1034 kPa at 200°C. Corrosion allowance is 4 mm, and joint efficiency is 0.85. What is the required thickness of the hemispherical heads?
4. Using the rules in Section VIII-1, determine the minimum required thickness of the flat end plate of a rectangular box header 200 mm by 400 mm with an internal pressure of 2500 kPa. Material used has a stress value of 103 MPa. Plate is integrally welded into place as per Fig UG-34(h). There is no corrosion allowance and no butt-welded joints in the plate.
5. Using the rules in Section I, determine if reinforcement is required for a 100 mm O.D. nozzle located in a cylindrical boiler drum. The nozzle abuts the vessel wall and is attached by a full-penetration weld. The I.D. of the drum is 780 mm. Thickness of the drum is 28.575 mm. Nozzle has a wall thickness of 3.5 mm. Drum material is SA-516-55, and nozzle material is SA-335-P1. Maximum allowable working pressure is 6000 kPa, and design temperature is 250°C. All joint efficiencies $E = 1$. Consider all outward welds to be 15 mm.
6. Determine the maximum allowable working pressure in kPa for a watertube boiler drum. Drum plate thickness is 50.8 mm with an inside radius of 500 mm. Longitudinal joint efficiency is 100%. Material is SA-516-55 and operating temperature is not to exceed 300°C. Pitch of the boiler tube holes in the drum is 140 mm as shown in Figure 7 (Figure PG-52.2). Diameter of the tube holes is 82.5 mm.





CHAPTER 2

ASME Code Calculations: Stayed Surfaces, Pressure Relief Valves and Furnaces

LEARNING OUTCOME

When you complete this chapter you should be able to:

Apply the appropriate formulae from A.S.M.E. Sections 1 and 8 to calculations involving pressure vessel stayed surfaces, safety and safety relief valves, and firetube boilers.

LEARNING OBJECTIVES

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

- 1. Calculate the required thickness and maximum allowable working pressure for braced and stayed surfaces in pressure vessels.*
- 2. Calculate the minimum required cross-sectional area of stays and staybolts in firetube boilers, including diagonal stays.*
- 3. Calculate the required size and capacity of pressure relief valves.*
- 4. Explain design considerations for various circular furnaces and calculate the required thickness of corrugated furnaces.*

NOTE: The formulas, calculations, and code references found in this chapter are from the 2015 ASME BPVC, which is reproduced in part in the PanGlobal 2018 ASME Academic Extract Volumes 1 and 2.



CHAPTER INTRODUCTION

The objective of this chapter is not to produce design engineers, but to provide power engineers with basic knowledge of the rationale of the codes.

This chapter uses ASME Sections I, and VIII-1. Each of these sections contains rules for braced and stayed surfaces, pressure relief valves, and furnaces or cylinders under external loads.

Consult the ASME BPVC Sections I and VIII Division 1 while studying this chapter. Paragraphs and Figures referenced with a Code section prefix (such as “Figure UG 34”) can be found in the ASME BPVC or the PanGlobal 2018 ASME Academic Extract Volumes 1 and 2.

OBJECTIVE 1

Calculate the required thickness and maximum allowable working pressure for braced and stayed surfaces in pressure vessels.

RELEVANT ASME CODE SECTIONS

In ASME Section I, the rules for stayed surfaces and staybolts can be found in Paragraphs PG-46 to PG-49, Paragraph PW-19, and Paragraphs PFT-22 to PFT-32.

In ASME Section VIII-1, the rules for stayed surfaces and staybolts can be found in Paragraphs UG-47 to UG-50, and Paragraph UW-19.

Stays are used in pressure vessels to carry part or all of the pressure loading when it is desirable to reduce the thickness of a tube sheet or other pressure restraining surface. Opposing surfaces are tied together by stays, staybolts, tubes, or baffles. These additional tensile members carry some of the pressure loading, permitting thinner shell materials to be used for a given MAWP.

FLAT STAYED SURFACES

The equation for flat-stayed surfaces is an adaptation of the flat head equation, with the diameter replaced by the distance between stays. In this case, the factor C represents the degree of restraint to rotation that the stay attachment provides.

The design thickness and pressure for stayed plates are calculated by applying the following formulae (see PG-46.1):

$$t = p \sqrt{\frac{P}{SC}} \quad (1.1)$$

$$P = \frac{t^2 SC}{p^2} \quad (1.2)$$

Where:

t = minimum required thickness of plate (mm)

p = maximum pitch measured between straight lines passing through the centres of the staybolts in different rows. The lines may be horizontal and vertical, or radial and circumferential (mm).

P = maximum allowable working pressure (MPa)

S = maximum allowable stress (MPa), from Section II, Part D, Subpart 1, Table 1A

C = a constant, the value of which depends on the staybolt end design, as follows:

C = 2.1 for welded stays or stays screwed through plates not over 11 mm thick, with ends riveted over

C = 2.2 for welded stays or stays screwed through plates over 11 mm thick, with ends riveted over

C = 2.5 for stays screwed through plates and fitted with single nuts outside the plate, or with inside and outside nuts, omitting washers



- $C = 2.8$ for stays with heads not less than 1.3 times the diameter of the stay, screwed through plates or made with a taper fit and having the heads formed on the stays before installing them, and with the threaded ends not riveted over; the heads having a true bearing on the plate.
- $C = 3.2$ for stays fitted with inside and outside nuts and outside washers, where the diameter of the washers is not less than $0.4p$ and the thickness of the washers is not less than the thickness (t) of the surface being stayed.

Paragraph **PG-46.2** states that the minimum thickness of plates to which stays may be applied, in other than cylindrical or spherical outer shell plates, is 8 mm except for welded construction covered by PW-19.

Example 1: Stayed flat plate - maximum pressure

Calculate the maximum allowable working pressure on stayed flat plates 12.5 mm thick, with staybolts attached by fusion welding and pitched 154 mm horizontally and vertically. The plate material is SA-516-55. The average temperature is 200°C.

Solution 1

Use equation 1.2 (see Section I, **PG-46.1**).

P = maximum allowable working pressure (MPa)

t = 12.5 mm

p = 154 mm

S = 108 MPa (from ASME II-D Table 1-A, SA-516-55 at 200°C)

C = 2.2 for welded stays or stays screwed through plates over 11 mm in thickness with ends riveted over

Solving:

$$\begin{aligned}
 P &= \frac{t^2 S C}{p^2} \\
 &= \frac{(12.5)^2 \times 108 \times 2.2}{(154)^2} \\
 &= \frac{37\,125}{23\,716} \\
 &= \mathbf{1.565\,MPa\,(Ans.)}
 \end{aligned}$$

Example 2: Stayed flat plate - thickness

Calculate the minimum required thickness for a stayed flat plate, with staybolts screwed through the plate and pitched at 185 mm horizontally and vertically. Plate material is SA-204-A. Maximum allowable working pressure is 6205 kPa. Maximum operating temperature is 300°C.

Solution 2

Use equation 1.1 (see Section I **PG-46.1**).

$$t = p \sqrt{\frac{P}{SC}}$$

Where:

$$P = 6.205 \text{ MPa}$$

$$S = 128 \text{ MPa}$$

$$p = 185 \text{ mm}$$

$$C = 2.2 \text{ (welded stays or stays screwed through plates over 11 mm in thickness with ends riveted over - assume that the plate will be greater than 11 mm thick.)}$$

Solving:

$$\begin{aligned} t &= p \sqrt{\frac{P}{SC}} \\ &= 185 \sqrt{\frac{6.205}{128 \times 2.2}} \\ &= 185 \times \sqrt{0.022} \\ &= 185 \times 0.148 \\ &= \mathbf{27.46 \text{ mm (Ans.)}} \end{aligned}$$

The minimum required thickness of 27.46 mm is greater than 11 mm, so 2.2 was the correct factor to use for C.

OBJECTIVE 2

Calculate the minimum required cross-sectional area of stays and staybolts in firetube boilers, including diagonal stays.

AREAS OF STAYS AND STAYBOLTS

In order to determine the minimum required cross-sectional area of boiler stays or staybolts, the primary guiding paragraph from ASME Section I is “**PG-49 Dimensions of Staybolts**”.

Paragraph PG-49.1 states:

The required area of a staybolt at its minimum cross-section shall be determined by dividing the load on the staybolt, computed in accordance with **PFT-26**, by the allowable stress value in accordance with Table 1A of Section II, Part D, Subpart 1 and multiplying the result by 1.10.

This can be represented by the equation:

$$\text{minimum of stay} = \frac{\text{load supported by stay}}{\text{allowable stress value of stay material}} \times 1.10$$

Before we can apply this equation, we must first determine the load supported by the stay. As mentioned in **PG-49.1**, the load is determined by applying **PFT-26.1**. The basic principle behind PFT-26.1 is that “force = pressure × area”.

Paragraph PFT-26.1 states:

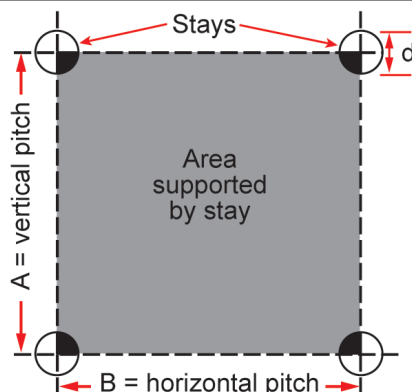
The full pitch dimensions of the stays shall be employed in determining the area to be supported by a stay, and the area occupied by the stay shall be deducted therefrom to obtain the **net area**. The product of the net area and the maximum allowable working pressure gives the load to be supported by the stay.

This can be represented by the equation:

$$\text{load supported by stay} = \text{net area supported stay} \times \text{MAWP}$$

The “net area” supported by the stay, as defined in **PFT - 26.1**, is the area of the full pitch minus the cross-sectional area of one stay. This is demonstrated below, in Figure 1. The full pitch area is $A \times B$. The cross-sectional area of the stay $0.7854 d^2$. The net area (shaded grey) is then $(A \times B) - 0.7854 d^2$.

Figure 1 – Area Supported by Stay



Note: PG-46.6 provides another method of determining the area supported by a staybolt. This is applied when staybolting is unsymmetrical by reason of interference with butt straps or other construction. In such a case, it is permissible to consider the load carried by each staybolt as the area calculated by taking the distance from the center of the spacing on one side of the staybolt to the center of the spacing on the other side.

Summary

To determine the minimum required area of a stay or staybolt, the following must be either given in the question or determined mathematically:

- the net area supported by the stay
- the MAWP of the stayed surface
- the maximum load on the stay, and
- the allowable stress value of the stay material.

Example 3: Finding minimum required stay area

A flat surface in a firetube boiler is stayed according to the design requirements of ASME Section I. The surface has 12 identical stays, evenly spaced on the surface and attached by welding. The **net** area supported is 0.8 m². The MAWP is 800 kPa. If the maximum operating temperature is 170°C and the allowable stress value the stay material is 118 MPa, what is the minimum required area of each stay?

Solution 3

$$\text{Net area supported by all stays} = 0.8 \text{ m}^2$$

$$\text{Net area supported by each stay} = \frac{0.8 \text{ m}^2 / \text{stay}}{12 \text{ stays}} = 0.067 \text{ m}^2$$

$$\text{Max. load on each stay} = \text{MAWP} \times \text{net area supported by stay}$$

$$= 800 \text{ kPa} \times 0.067 \text{ m}^2$$

$$= 53.6 \text{ kN}$$

$$\text{Minimum area of each stay} = \frac{\text{Load supported by stay}}{S} \times 1.10$$

$$= \frac{53.6 \text{ kN}}{118 \text{ 000 kPa}} \times 1.10$$

$$= 0.000499 \text{ m}^2$$

$$= 499 \text{ mm}^2 \text{ (Ans.)}$$

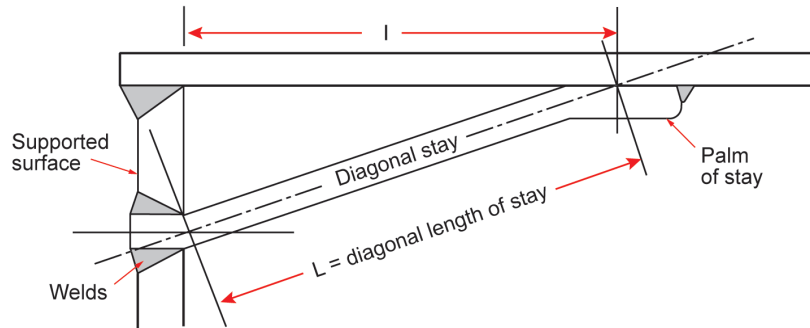
AREA OF DIAGONAL STAYS

The preceding discussion and calculations referencing PG-49.1 and PFT-26.1, are applied to “through” stays (also called direct stays) and staybolts, which are perpendicular to the surface being stayed. Diagonal stays are not mounted perpendicular to the stayed surfaces. They are used when a through stay would block access through a manhole or other inspection opening. Commonly, they are used to support the unstayed surfaces of firetube boiler tubesheets.



ASME Section I, PFT-32 covers diagonal stays. **Figure PFT-32** (similar to Figure 2 below) shows the arrangement of a typical diagonal stay.

Figure 2 – Diagonal Stay



PFT-32.1 gives the procedure to calculate the area of a diagonal stay. It says:

To determine the required area of a diagonal stay, multiply the area of a direct stay required to support the surface by the slant or diagonal length of the stay, and divide this product by the length of the line drawn at right angles to the surface supported to the center of the palm of the diagonal stay, as follows:

$$A = \frac{a L}{l}$$

Where:

A = sectional area of diagonal stay

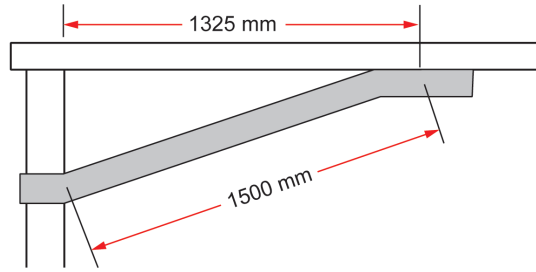
a = sectional area of direct stay

L = length of diagonal stay as indicated in Figure PFT-32

l = length of line drawn at right angles to boiler head or surface supported to center of palm of diagonal stay, as indicated in Figure PFT-32 (mm)

Example 4

If the stays in Example 3 are attached diagonally and all stated conditions remain the same, what must the minimum diameter of each stay be, given the dimensions shown in this diagram?



Solution 4

First, calculate the dimension of a direct stay. This has already been done in Example 3, and is given as 499 mm². This is the value “a”.

The minimum area of each diagonal stay is found by substituting the values given for L and l:

$$\begin{aligned} A &= \frac{a L}{l} \\ &= \frac{499 \text{ mm}^2 \times 1500 \text{ mm}}{1325 \text{ mm}} \\ &= 564.91 \text{ mm}^2 \end{aligned}$$

The diameter can then be found as follows:

$$\begin{aligned} d &= \sqrt{\frac{A}{0.7854}} \\ &= \sqrt{\frac{564.91 \text{ mm}^2}{0.7854}} \\ &= 26.8 \text{ mm (Ans.)} \end{aligned}$$

PFT-32.2 gives an alternative method for determining the area of diagonal stays used to support tubesheets, which can be applied when L is not more than $1.15 \times l$. This paragraph permits diagonal stays to be calculated as if they were direct stays, but using only 90% of the allowable stress given in ASME II-D.

This method could have been used in Example 4 above since $1.15 \times l = 1523.75$, and ‘L’ (= 1500 mm) is not greater than 1523.75. In this case, the minimum required stay area would be:

$$\begin{aligned} \text{Minimum area of each stay} &= \frac{\text{Load supported by stay}}{0.90 \times S} \times 1.10 \\ &= \frac{53.6 \text{ kN}}{0.90 \times 118\,000 \text{ kPa}} \times 1.10 \\ &= 0.000\,555 \text{ m}^2 \\ &= 555 \text{ mm}^2 \end{aligned}$$

Note: Specific rules for the design and attachment by welding of diagonal stays are found in ASME Section I, **PW-19**.



OBJECTIVE 3

Calculate the required size and capacity of pressure relief valves.

The most important and critical valves on a boiler are the **pressure relief valves (PRVs)**. Their purpose is to protect the boiler by ensuring the pressure never exceeds the maximum allowable working pressure. When the valves open, they must be able to release all of the steam that the boiler is capable of generating, at maximum firing rate, without an excessive increase in boiler pressure. The overpressure protection requirements for boilers are outlined in ASME I Paragraph **PG-67**.

ASME Section I uses the term “pressure relief valve” as a general term, which covers safety valves, relief valves, and safety relief valves. The following are excerpts from ASME I Paragraph PG-67.

Paragraph **PG-67.1** states:

Each boiler shall have at least one pressure relief valve and if it has more than 47 m² of bare tube heating surface, or if an electric boiler has a power input more than 1100 kW, it shall have two or more pressure relief valves. For a boiler with combined bare tube and extended water-heating surface exceeding 47 m², two or more pressure relief valves are required only if the design steam generating capacity of the boiler exceeds 1800 kg/hr.

Paragraph **PG-67.2** states:

The pressure relief valve capacity for each boiler (except as noted in PG-67.4) shall be such that the pressure relief valve, or valves will discharge all the steam that can be generated by the boiler without allowing the pressure to rise more than 6% above the highest pressure at which any valve is set and in no case to more than 6% above the maximum allowable working pressure.

Paragraph **PG-67.2.1** states:

The minimum required relieving capacity of the pressure relief valves for all types of boilers shall be not less than the maximum designed steaming capacity at the MAWP of the boiler, as determined by the Manufacturer.

Paragraph **PG-69** contains the rules and capacity tests that a pressure relief valve manufacturer must meet in order to obtain an ASME Code Symbol.

Paragraph **PG-70** states that, subject to the minimum number required by **PG-67.1**, the number of PRVs required shall be determined on the basis of the maximum designed steaming capacity, as determined by the boiler manufacturer, and the relieving capacity marked on the valves by the manufacturer.

Section I Nonmandatory Appendix A, Paragraphs A-12 to A-17 illustrate the method of checking pressure relief valve capacity by calculating the maximum amount of fuel that can be burned per hour.

Using the formula from **Nonmandatory Appendix A, Paragraph A-12**:

$$W = \frac{C \times H \times 0.75}{2558} \quad (2.1)$$

Where:

W = mass of steam generated (kg/hr)

C = total mass or volume of fuel burned/hr at time of maximum firing,
(kg/hr or m³/hr)

H = heat of combustion of fuel (kJ/kg or kJ/m³) from A-17

The sum of the capacities marked on the pressure relief valves shall be equal to or greater than W .

Example 5: Relieving Capacity of Pressure Relief Valves

A boiler at the time of maximum firing uses 730 m³ of natural gas per hour. Boiler pressure is 1550 kPa gauge. What is the minimum combined capacity of the pressure relief valves?

Solution 5

From the table in A-17, natural gas has an H value of 35 700 kJ/m³.

$$\begin{aligned} W &= \frac{C \times H \times 0.75}{2558} \\ &= \frac{730 \times 35\,700 \times 0.75}{2558} \\ &= 7641 \text{ kg of steam per hour (Ans.)} \end{aligned}$$

Paragraph A-17 lists some specific heating values for various types of fuels. The heating value of the fuel must be known to solve equations determining the mass of steam that can be generated in a boiler.

Section I, **Nonmandatory Appendix A-44** states:

The minimum pressure relief valve relieving capacity for other than electric boilers, waste heat boilers, organic fluid vaporizers, and forced-flow steam generators with no fixed steam and waterline, when provided in accordance with **PG-67.4.3**, may be estimated on the basis of the kilogram of steam generated per hour per square metre of boiler heating surface and waterwall heating surface, as given in **Table A-44**.

Note that this is a simplistic method of estimation that may be used by boiler designers. A-44 addresses the limitations of this method:

In many cases, a greater relieving capacity of pressure relief valves will have to be provided than that estimated using Table A-44, in order to meet the requirements of the first paragraph of PG-67.2.

Section I, **Nonmandatory Appendix A-46** lists three methods that can be used to check the pressure relief valve capacity if the capacity cannot be determined or verified. There are limitations on the methods that can be used, based on specific types of boiler designs. These methods are as follows:

1. By performing an accumulation test by shutting off all other steam-discharge outlets from the boiler and forcing the fires to maximum.
2. By measuring the maximum amount of fuel that can be burned, and calculating the evaporative capacity upon the basis of the heating value of the fuel.
3. By determining the maximum evaporative capacity by measuring the feedwater. The sum of the pressure relief valve capacities marked on the valves shall be equal to or greater than the maximum evaporative capacity of the boiler.

OBJECTIVE 4

Explain design considerations for various circular furnaces and calculate the required thickness of corrugated furnaces.

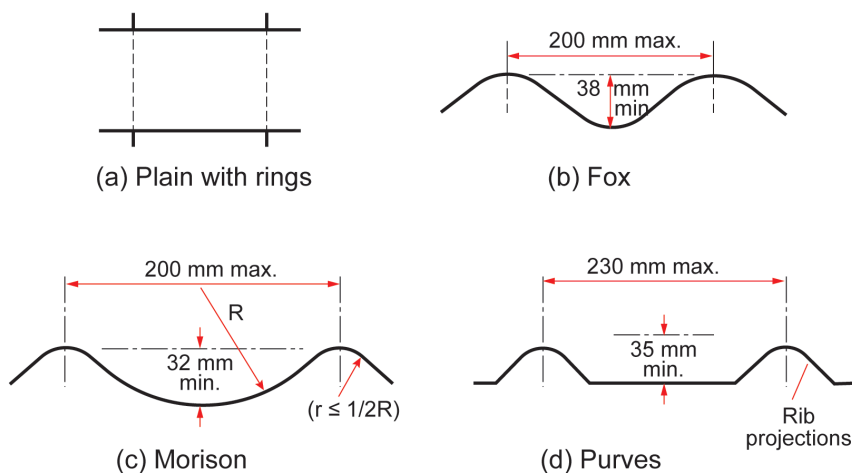
CIRCULAR FURNACES

Circular furnaces such as those in some firetube boilers are subjected to external pressure. This pressure produces compressive stresses that could cause the furnace to collapse if insufficient wall thickness or incorrect design are used.

Many different designs have been implemented over the years to provide sufficient strength to circular furnaces to withstand the external pressure. In ASME Section I, acceptable designs include plain circular furnaces (**PFT-15**), ring-reinforced furnaces (**PFT-17**), and several designs of corrugated furnaces (**PFT-18**).

Figure 3 below shows examples of acceptable furnace designs, described in **PFT-18.1**.

Figure 3 – Circular Furnace Designs



Note: The dimensions shown in Figure 3 are the dimensional limits for the applicable value of C listed and described in **PFT-18.1**.

PLAIN FURNACES

Plain circular furnaces are simple cylinders. They are often used because of the simplicity of their construction and their relatively low cost. For plain circular furnaces in firetube boilers, Section I Paragraph **PFT-15.1** specifies the minimum furnace wall thickness as 8 mm. (Note: ASME Section IV specifies that the thickness may not be less than 6 mm. The difference in thickness is due to heating boilers being constructed for and operating at low pressures). Paragraph **PFT-15.2** states that the maximum allowable working pressure must be determined according to **PG-28.3**.

PG-28.3 outlines procedures to determine the maximum allowable working pressure or minimum thickness of cylindrical components under external pressure, including firetubes, flues, and plain circular furnaces. To support the use of PG-28.3, charts are provided in ASME Section II, Part D, Subpart 3. These include the following:

- Figure G Geometric Chart for Components Under External or Compressive Loadings
- Figures CS-1 through CS-6 for Carbon or Low Alloy Steels
- Figures for high strength steels, austenitic steels, cast iron, ductile iron, and others.

Ring-reinforced furnaces (see Figure 3(a)) are plain furnaces with stiffening rings attached around the outside of the plain furnace cylinder. Requirements for this design are covered in Section I, **PFT-17**.

Plain circular and ring-reinforced furnace calculations are beyond the scope of Second Class Power Engineering.

CORRUGATED FURNACES

Corrugated furnaces have the following advantages over plain furnaces:

1. Stronger than a plain furnace of the same dimensions
2. Better expansion allowance using corrugations or ribs.
3. More surface area for the same length, therefore better heat transfer.

The rules for corrugated furnaces were originally developed in England in the late 1800s. Since then, riveted seams and joints have been replaced by fusion welding, which has improved the designs considerably.

Five corrugation designs are currently recognized in ASME Section I, **PFT-18**. They are named after the original designers or manufacturers: Leeds, Morison, Fox, Purves, and Brown. Figure 3 shows the general shape of the Fox and Morison corrugations. The Leeds and Brown designs are similar, with slightly different corrugation sizes. The Purves differs in that it has rib projections with plain sections between them.

ASME Section I, **PFT-18** contains the rules for determining the maximum allowable working pressure for these common types of corrugated furnaces, having plain portions at each end not exceeding 230 mm in length.

The formula to apply is found in **PFT-18.1**:

$$P = \frac{C t}{D}$$

Where:

P = maximum allowable working pressure (MPa)

t = thickness in mm (not less than 8 mm for Leeds, Morison, Fox, and Brown furnaces, and not less than 11 mm for Purves furnaces)

D = mean diameter, in mm

Note: The mean diameter of the Morison furnace may be taken as the least inside diameter plus 50 mm.

C = a constant, the value of which depends on the type of furnace, as follows:

C = 119 for Leeds furnaces, when corrugations are not more than 200 mm from centre to centre and not less than 57 mm deep



- C = 108 for Morison furnaces, when corrugations are not more than 200 mm from centre to centre and not less than 32 mm deep, and the radius of the outer corrugation r is not more than one-half of the radius of the suspension curve R (see Figure 3 and Figure PFT-18.1)
- C = 97 for Fox furnaces, when corrugations are not more than 200 mm from centre to centre and not less than 38 mm deep
- C = 97 for Purves furnaces, when rib projections are not more than 230 mm from centre to centre and not less than 35 mm deep
- C = 97 for Brown furnaces, when corrugations are not more than 230 mm from centre to centre and not less than 41 mm deep

Example 6: Wall thickness of a corrugated furnace

A Brown corrugated furnace of 1065 mm mean diameter, fitted with plain end, 216 mm in length, is required to operate at a pressure of 860 kPa. Corrugations are 222 mm from centre to centre and 41 mm deep. What is the required thickness of the furnace wall?

Solution 6

First, compare the dimensions of the corrugations and plain ends to the criteria for Brown furnaces in **PFT-18.1**. The depth of corrugations (41 mm), the distance between corrugations (222 mm), and the length of the plain ends (216 mm) meet the criteria for Brown furnaces; therefore, $C = 97$.

The required thickness can be calculated transposing the equation from **PFT- 18.1** to solve for t .

$$P = 860 \text{ kPa (0.86 MPa)}$$

$$D = 1065 \text{ mm}$$

$$C = 97 \text{ (Brown furnace with corrugations not more than 230 mm from centre to centre and not less than 41 mm deep)}$$

Solving:

$$\begin{aligned} t &= \frac{PD}{C} \\ &= \frac{0.86 \times 1065}{97} \\ &= 9.44 \text{ mm (Ans.)} \end{aligned}$$

According the thickness definition in **PFT-18.1**, a Brown furnace must not be less than 8 mm thick. **Because the calculated thickness (9.44 mm) exceeds the minimum requirement (8 mm), the thickness of the furnace is 9.44 mm. (Ans.)**

Note: In this example, the plain ends are less than 230 mm long. If the plain ends of corrugated furnaces exceed 230 mm in length, additional plain circular furnace thickness calculations must be performed (according to **PG-28.3**) for the plain ends.

CHAPTER QUESTIONS

The following questions provide the candidate with experience using the ASME Codes.

1. A flat plate is stayed with welded staybolts equally pitched both horizontally and vertically. Plate is 12.2 mm thick and is made of SA-285-B material. Maximum allowable pressure is 865 kPa. Operating temperature is 250°C. Calculate the maximum permissible pitch of the stays.
2. A boiler is to be converted from burning pulverized semi-bituminous coal to natural gas. At maximum load the boiler burns coal at a rate of 5.5 tonnes per hour. What is the maximum amount of natural gas that can be burned per hour if the safety valves are re-rated to 3% above their present capacity?
3. An internal furnace is built using the Fox corrugation design. Furnace has a mean diameter of 1118 mm, a maximum working temperature of 370°C, and an external design pressure of 1375 kPa. Corrugations are 152.4 mm centre to centre and have a suspension curve depth of 38 mm. Length of the furnace is 2.5 m. Furnace material is carbon steel with a minimum yield strength of 207 MPa. What is the minimum required thickness of the furnace tube?



CHAPTER 3

Boiler and Pressure Vessel Legislation

LEARNING OUTCOME

When you complete this chapter you should be able to:

Describe the components and application of boiler and pressure vessel legislation within Canadian jurisdictions.

LEARNING OBJECTIVES

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

- 1. Identify the types and sources of Laws and the levels and scope of the Courts.*
- 2. Define Statutory Delegation of Powers as they apply to the Boilers and Pressure Vessels Act.*
- 3. Describe the authority that Safety Officers (Inspectors) have within their jurisdiction.*
- 4. Determine what are the offences and penalties under the Act and the appeal process.*
- 5. Describe the typical Regulations under the Boilers and Pressure Vessels Act.*
- 6. Describe the typical Codes and Standards referenced by the Boilers and Pressure Vessels Act.*



CHAPTER INTRODUCTION

This chapter has been written to give the Second Class Power Engineering candidate a broader understanding of the laws that govern their duties and responsibilities. It should be read alongside the Boilers and Pressure Vessels Acts and Regulations of the examination candidate's jurisdiction. Power Engineers must familiarize themselves with legislative changes, and with the legislation of other jurisdictions if relocating.

Second Class Power Engineering candidates must know their legal responsibilities, and the penalties for contravening laws. As well, they should have a good working knowledge and understanding of the codes and standards referred to in legislation. Most Power Engineers are well-versed with ASME Section I, CSA B51, and B52; however, there are many other codes and standards that directly apply to Power Engineering.

OBJECTIVE 1

Identify the types and sources of Laws and the levels and scope of the Courts.

TYPES OF LAW

Power Engineers know that jurisdictional Boilers and Pressure Vessels Acts and Regulations mandate our positions and responsibilities. The Act is law. When we think of the law we seldom think of types of law. However, it is important to differentiate between the various types of law.

There are four main types of law that are of interest to Power Engineers:

- constitutional law
- civil law
- criminal, quasi-criminal, or regulatory law
- administrative law.

Constitutional Law

Constitutional law involves the relationships between the various legal components that exist in Canada. For example, constitutional law considers the powers of the federal government, provincial governments, and local authorities such as municipal governments.

Civil Law

Civil law may be defined as private law, which exists between parties:

Civil law is often referred to not as a system, but as, essentially, private law. In this sense, civil law is often contrasted with criminal law. In the latter context, the civil law refers to, for example, rights and remedies in connection with the law of contracts, torts, and real property. In other words, here, the civil law is concerned with rights and duties in connection with one's fellow citizens in a private capacity. This is contrasted with criminal law, which is concerned with the rights and duties enjoyed by the subject in connection with the state. (Gall, 25)

Criminal, Quasi-Criminal, or Regulatory Law

Law that may be termed criminal, quasi-criminal, or regulatory involves offences “against the state, against the people and against the public interest.” (Gall, 20). Criminal law is law referred to in the Criminal Code of Canada. Quasi-criminal law involves penal consequences (such as imprisonment, fines, or both). This includes a variety of laws ranging from the federal Narcotics Control Act to provincial Acts, such as the Boilers and Pressure Vessels Act, Alberta's Safety Codes Act, and British Columbia's Safety Standards Act.

Administrative Law

The study of safety services law has traditionally focused on civil law, with some consideration given to criminal and quasi-criminal law. Another area of law that plays an important role with respect to Power Engineering is administrative law. Administrative law has been defined as follows:

Administrative law deals with the legal limitations on the actions of governmental officials, and on the remedies available to anyone affected by a transgression of these limits. The subject invariably involves the question of the lawful authority of an official to do a particular act which, in the absence of such authority, might well be illegal (or *ultra vires*) and give rise to an actionable wrong. (Jones and de Villars, 3)

Ultra vires is a legal term which means “beyond a person's power or authority.”



SOURCES OF LAW

Each type of law discussed above comes from a variety of sources. Generally, the law comes from two primary sources: legislation and courts. The body of law derived from legislation is termed **statute law**, whereas the courts establish **common law** or **case precedent law**.

Legislative

There are two principal types of legislation that are of concern to Power Engineers:

- primary legislation
- subordinate legislation.

Primary Legislation

The legislative body as a whole enacts **primary legislation**. Primary legislation is usually called an **Act**. For example, a “Boilers and Pressure Vessels Act” would be primary legislation, enacted by the legislature.

Subordinate Legislation

Subordinate legislation is a form of legislation that permits legislative activity by a body that is subordinate to the legislative body. This subordinate legislation comes in a variety of forms including regulations, orders-in-council, and municipal bylaws. The nature and purpose of subordinate legislation may be described as follows:

In recent years there has been a major proliferation of legislative enactments at all levels of government. Because Parliament and the various provincial legislatures cannot possibly deal with every matter, and indeed lack the requisite expertise to do so, a common legislative practice is for the sovereign legislative body, be it Parliament or a provincial legislature, to enact governing enabling legislation. Under that enabling legislation, the power to make statutory instruments - orders in council, regulations, by laws, etc. - is delegated to an inferior body. That inferior body may be the cabinet, a minister of the cabinet, an administrative tribunal, a municipal council, or one of the many other forms of inferior legislative authority. The inferior body may then enact subordinate legislation, in accordance with its terms of reference as set out in the enabling statute. In doing so, it may not, of course, exceed its jurisdiction as provided in the enabling statute. (Gall, 38)

Regulations

Of particular interest to Power Engineers is subordinate legislation (“Regulations”) passed under the authority of a “Boilers and Pressure Vessels Act” or “Safety Codes Act”. For example, Section 65 of the Alberta Safety Codes Act empowers the Lieutenant Governor of Alberta in Council (provincial cabinet) to pass regulations relating to a wide range of subjects under the Act.

Municipal Bylaws

Every province and territory in Canada has local governments, commonly called municipalities, which are empowered to carry out such government functions as the provincial or territorial legislation allows. This includes the power to pass legislation with respect to local government matters. This legislation is known as municipal bylaw, and is of the same force and effect as provincial and territorial legislation. Examples of this type of legislation include municipal land use bylaws and fire and emergency services bylaws.

Judicial

Interpretation of Legislation

The first role of the courts is to interpret the legislation enacted by legislators. Despite the best attempts of those who draft legislation, legislation may be unclear and open to interpretation.

A classic example occurred when the Canadian Charter of Rights and Freedoms was introduced into the Canadian Constitution in 1982. At the time of its introduction, there was considerable controversy about whether the charter applied to all matters in Canada (both public and private sector), or only to governmental affairs. Eventually, the courts were called upon to resolve the issue, with the Supreme Court of Canada adopting the narrower interpretation of the application of the charter, which saw it as applying only to government affairs. Thus, when reading legislation, it is also important to review case law to determine how the courts have interpreted that legislation.

Common Law

The second role of the courts is to create law where legislation does not exist. This most often occurs in civil law, such as contract law and tort law. This is known as the common law, and is found solely in the case law. For example, the legal right for a person to sue a government officer for his or her actions during the course of their duties will not be found in the Boilers and Pressure Vessels Act. The authority for such action is found in the legal principle of **tort** set down by the courts in many cases over the years. The principle holds that if the actions of an individual, corporation, or government cause injury or damage to another person (not arising as the result of a contract), and that injury or damage may be compensated for, the injured or damaged party should be compensated for his or her loss by the party who caused the loss.

CONSTITUTIONAL FOUNDATION

Definition of Constitutional Law

Constitutional law has been defined as

The law prescribing the exercise of power by the organs of a State. It explains which organs can exercise legislative power (making new laws), executive power, (implementing the laws) and judicial power (adjudicating disputes) and what the limitations on those powers are. (Hogg)

Another authority further describes constitutional law as follows:

In its broadest sense, Constitutional Law comprises all of the fundamental rules for determining who and which institutions have the right to make laws for the government of our society; it is 'a law for the making of laws.' (Jones and de Villars)

The Constitution in Canada

Constitutional parameters are contained in the constitution of a country. In Canada, as in Great Britain, the constitution is a set of laws and principles contained in a number of documents. The United States of America, on the other hand, has a single document with several amendments. In Canada, the documents making up the constitution are defined in the Constitution Act, 1982 (Section 52(2)) which says:

The Constitution of Canada includes:

- (a) The Canada Act 1982, including this Act;
- (b) The Acts and Orders referred to in the schedule; and
- (c) Any amendments to any Act or order referred to in paragraph (a) or (b)



The Canada Act 1982 is an Act of the Parliament of Canada, which assumed the power previously held by the Parliament of the United Kingdom to legislate for Canada. A schedule to this Act is the Constitution Act, 1982, that contains the Canadian Charter of Rights and Freedoms: an important document for legislators and enforcement officials as all subordinate laws and associated regulations must be in harmony with this aspect of constitutional law.

The schedule to the Canada Act 1982, among other Acts and orders-in-council, contains the Constitution Act, 1867 (the British North America Act, 1867) which is still the document that distributes power between the federal Parliament and provincial legislatures. The amendments include any amendments made to the Canada Act 1982 or the Constitution Act, 1982.

A constitution is the authoritative law of a country with which all other laws must be in harmony and to which all other laws are subordinate. A constitution is therefore characterized as the supreme law of a country. Because changes to the constitution will have far-reaching effects, the process for change is complex. As this document is resistant to change, it is said to be **entrenched**.

Powers of the Legislative Bodies

The Constitution Act, 1867 recognizes two levels of government in Canada and prescribes the powers that each may exercise. Thus, the federal Parliament under Section 91 has certain prescribed powers, while the jurisdiction of the provincial legislatures is described in Sections 92 to 126. The authority for provincial jurisdiction of fire, emergency, and safety services is found in several subsections of Section 92:

92. In each Province, the Legislature may exclusively make Laws in relation to Matters coming within the Classes of Subject next hereinafter enumerated; that is to say,
 5. The Management and Sale of the Public Lands belonging to the Province and of the Timber and Wood thereon. ...
 10. Local Works and Undertakings other than such as are of the following Classes:
 - (a) Lines of Steam or other Ships, Railways, Canals, Telegraphs and other Works and Undertakings connecting the Province with any other or others of the Provinces, or extending beyond the limits of the Province;
 - (b) Lines of Steam Ships between the province and any British or Foreign country;
 - (c) Such Works as, although wholly situated within the Province, are before or after their Execution declared by the parliament of Canada to be for the general Advantage of Canada or for the Advantage of Two or more of the Provinces. (National parks, Military Bases and Canada Post.) ...
 13. Property and Civil Rights in the Province. ...
 15. The Imposition of Punishment by Fine, Penalty, or Imprisonment for enforcing any law of the Province made in relation to any matter coming within any of the Classes of Subjects enumerated in this Section.
 16. Generally all Matters of a merely local or private Nature in the Province.

While the division of powers outlined in the Constitution Act, 1867 is quite extensive, there are situations not covered by the Act. These left over, or residual, areas of responsibility are addressed by the concept of residual powers. Two categories are identified: federal **residual powers** and provincial residual powers.

In the preamble to Section 91 of the Constitution Act, 1867, powers are given to the federal Parliament “to make laws for the Peace, Order and Good Government of Canada.” The courts have developed three tests for this **POGG power**, one of which must be met to give the federal government the authority in the matter.

1. **Gap Test:** If there is a gap in the constitutional distribution of powers, this test can apply. It requires that the matter under consideration fall partly within an existing Class of Subject as already discussed. However, it also requires that the Class of Subject fails to deal completely with the matter. An example is the constitutional jurisdiction of provinces with respect to the incorporation of companies with provincial objects. No such statement is made for federal jurisdiction for companies with federal objects, but the courts have held this test to justify the federal jurisdiction in this matter.
2. **National Concern Test:** Matters of national, rather than provincial, concern not covered by the Constitution fall under federal jurisdiction if this test is met. An example of this is that aeronautics (air travel), which is not specifically addressed in the Constitution, is a matter of national concern and therefore should fall under federal jurisdiction.
3. **Emergency Test:** The federal government can use the POGG principle in cases of emergency. An example of the use of this power is court support for the authority to enact emergency legislation, which has included the War Measures Act and the Anti-Inflation Act.

Provincial residual power is found in Subsection 92(16) of the Constitution Act, 1867 which states

92. In each Province the Legislature may exclusively make Laws in relation to Matters coming within the Classes of Subject next hereinafter enumerated; that is to say ...
16. Generally all Matters of a merely local or private Nature in the Province.

Municipal Governments

Other levels of government are not mentioned in the Constitution, except for the provision in Subsection 92(8), which provides that provincial legislatures may create “municipal institutions in the province.” These municipal institutions have been interpreted by the courts as local governmental bodies concerned with the needs, health, safety, comfort, and orderly government of organized communities. They are generally referred to as local public authorities. Examples of such municipal institutions include municipalities, school boards and districts, regional public health boards, and other administrative boards, commissions, councils, and tribunals.

Municipal institutions, as subordinate governmental bodies, have powers subordinate to the provincial legislature. One of the powers given to municipal governments is the power to pass bylaws, which is legislation subordinate to provincial enactments. Typical examples can be found in the various Boilers and Pressure Vessels Acts, such as:

A bylaw of a municipality that purports to regulate a matter that is regulated by this Act is inoperative.

Notwithstanding this provision, the Act often goes on to state that municipalities can make bylaws “respecting the carrying out of its powers and duties as an accredited municipality.”

Corporations

Authority for code compliance monitoring and management can be granted to corporations, such as Technical Safety BC, the Alberta Boiler Safety Association (ABSA), the Technical Safety Authority of Saskatchewan (TSask), and Ontario’s Technical Standards and Safety Association (TSSA).

This places such organizations in a similar position to municipalities, although their authority is not derived by specific reference in the Constitution. Rather, it is derived under the provision in the Constitution allowing provinces the jurisdiction for “the incorporation of companies with provincial objects.” The suggestion is that such companies are creatures of the provincial government and can therefore be assigned powers within provincial jurisdiction although, in practice, a corporation does not have to be incorporated under provincial law.



THE COURT SYSTEM

The structure of the Canadian legal system is established by the Constitution, which allows for the following classification of courts for the administration of justice.

PROVINCIAL COURTS

The power over the administration of justice in the provinces is given to the provinces by Section 92(14) of the Constitution Act, 1867 which states:

92. In each Province the Legislature may exclusively make laws in relation to Matters coming within the Classes of Subject next hereinafter enumerated; that is to say, ...
14. The Administration of Justice in the Province, including the Constitution, Maintenance, and Organization of Provincial Courts, both of Civil and of Criminal Jurisdiction, and including Procedure in Civil Matters in those Courts.

Every province has used this power to enact legislation establishing provincial courts and to appoint judges to these courts. Provinces have divided the provincial court into specialized divisions. Of particular interest to Power Engineers are the civil division (often called small claims court) and the criminal division.

Civil Division

Subject to a number of exceptions, the jurisdiction of the civil division of the provincial court may include claims for damages, debt, or both, not exceeding \$4000 (updated from time to time).

Criminal Division

The jurisdiction of the criminal division of the provincial court that is of interest to Power Engineers includes the following:

- a) Offences under provincial legislation
- b) Summary conviction offences
- c) Indictable offences under Section 553 of the Criminal Code
- d) Indictable offences by election of a Jury or by the judge alone
- e) Preliminary hearings

SUPERIOR COURTS

While Section 92(14) of the Constitution Act, 1867 grants power over the administration of justice to the provinces, Section 96 grants to the federal Parliament the power to appoint the judges of the superior courts in each province:

1. The Governor General shall appoint the Judges of the Superior, District, and County Courts in each province, except those of the Courts of Probate in Nova Scotia and New Brunswick.

COURT OF QUEEN'S BENCH

Such courts are often collectively called Section 96 Courts and operate as the Court of Queen's Bench. The jurisdictional scope of the Court of Queen's Bench is broad. The following areas are of interest to Power Engineers:

- a) Indictable offences under Section 469 of the Criminal Code of Canada.
- b) Indictable offences by election (jury or judge alone)
- c) Appeals of summary conviction offences
- d) All civil matters in excess of \$4000
- e) Appeals from small claims court
- f) Administrative law jurisdiction with respect to applications for judicial review or statutory rights of appeal of administrative decisions

COURT OF APPEAL

The superior provincial appeal court is the Court of Appeal. The jurisdiction of the Court of Appeal that is of interest to Power Engineers includes those listed below:

- a) Appeals of all criminal cases
- b) Appeals of all civil matters
- c) Applications for new trials
- d) Appeals of administrative law decisions with respect to applications for judicial review or statutory rights of appeal of administrative decisions

FEDERAL COURTS

Section 101 of the Constitution Act, 1867 provides:

The Parliament of Canada may, notwithstanding anything in this Act, from Time to Time provide for the Constitution, Maintenance and Organization of a General Court of Appeal for Canada, and for the Establishment of any additional Courts for the better Administration of the Laws of Canada.

Pursuant to this power, the federal Parliament has established many judicial bodies, including the Federal Court of Canada and the Supreme Court of Canada.

Federal Court of Canada

The Federal Court of Canada, which replaced the Exchequer Court of Canada, was established by the federal Parliament to hear certain matters which fell within federal constitutional jurisdiction. The Federal Court of Canada consists of a trial and an appeal division, which are staffed by fourteen federally appointed justices, one of whom serves as the chief justice of the court.



Trial Division

The jurisdiction of the trial division of the Federal Court of Canada, which is of interest to Power Engineers, includes the following:

- a) Exclusive jurisdiction with respect to:
 - i) Claims against the Crown;
 - ii) Granting equitable relief against any federal board, commission, or other tribunal;
 - iii) Hearing matters of copyright, trademark, industrial design, and patents of invention; and
 - iv) Applications for writs in relation to anyone in the Canadian Armed Forces stationed outside Canada.
- b) Residual jurisdiction regarding:
 - i) Matters where no other Canadian court has jurisdiction; and
 - ii) Matters within the jurisdiction of the Federal Court which are not specifically assigned to the appeal division.
- c) Shared (concurrent) jurisdiction with other courts over the following:
 - i) Admiralty;
 - ii) Aeronautics;
 - iii) Claims against officers or servants of the Crown for acts or omissions committed in carrying out their duties;
 - iv) Crown claims; and
 - v) Interprovincial works and undertakings.

Appeal Division

The jurisdiction of the appeal division of the Federal Court of Canada, which is of interest to safety services, includes the following areas:

- a) Appeals from the trial division of the Federal Court
- b) Applications to renew and set aside decisions of federal administrative tribunals such as boards and commissions
- c) Reference cases with respect to questions of law, jurisdiction, or practice referred by federal administrative tribunals
- d) Statutory appeals under a variety of federal Acts

Supreme Court of Canada

The Supreme Court of Canada was established in 1875. Appeals to the judicial committee of the Privy Council in Great Britain were abolished in 1949. Then, the Supreme Court of Canada assumed the role as the highest court of appeal for all criminal and civil law cases in Canada. The Supreme Court of Canada comprises nine federally appointed justices, one of whom serves as the Chief Justice of Canada. The jurisdiction of the Supreme Court of Canada differs between civil and criminal cases. Each of these jurisdictions is summarized below.

Civil Cases

Leave of the Supreme Court to appeal decisions of a provincial court of appeal is required. Such leave will only be given for matters of public importance, or important issues of law, or of mixed law and fact.

Criminal Cases

The Supreme Court may hear appeals from decisions of a provincial court of appeal with respect to the following types of offences:

- a) Indictable offences, with leave, on questions of law where there has been no dissenting opinion in the provincial court of appeal
- b) Indictable offences, without leave, on questions of law where there has been a dissenting opinion in the provincial court of appeal
- c) Summary conviction offences, with leave, on questions of law

Reference Cases

The Supreme Court of Canada also has the power to give opinions on constitutional and other matters which involve the factors listed below:

- a) The interpretation of constitutional legislation
- b) The interpretation of federal and provincial legislation
- c) The jurisdiction of the federal Parliament and the provincial legislature
- d) Any matter which is referred to the Supreme Court pursuant to the Supreme Court Act

Cases in which the opinion of the Supreme Court of Canada is sought with respect to these matters are known as **reference cases** or simply **references**. These cases are said to be referred to the Court for its consideration.



OBJECTIVE 2

Define Statutory Delegation of Powers as they apply to the Boilers and Pressure Vessels Act.

STATUTORY DELEGATION OF POWERS

The federal, provincial, and territorial governments have delegated a wide range of powers with respect to Power Engineers. Those entities that receive such delegated powers are referred to in legal terminology as **statutory delegates**.

The rationale for such delegation may include the following factors:

- a) The size of the business of government means that neither the federal Parliament nor the provincial/territorial legislatures can deal with everything.
- b) Many government activities are technical in nature, and legislation should contain only broad principles.
- c) The delegation of power to an administrator allows greater flexibility in applying broad statutory provisions to changing circumstances.
- d) Devising a general rule to deal with all cases may not be possible, and a solution thus may be more conveniently determined by the discretion of a delegate.
- e) The need for rapid governmental action may require a faster administrative response than the legislative amendment process can accommodate.
- f) Innovation and experimentation in solving social problems may not be possible if legislation is required.
- g) When a person or persons are required to apply legislation, then they must have legal authority to do so, and this authority is conveyed through delegation.
- h) Emergencies may require broad delegation of powers, respecting a wide range of matters, which legislation would normally address.

There are three types of functions concerning safety services that the federal, provincial, and territorial governments have delegated. A description of each function follows.

Legislative

Delegated legislative functions refer to the power to enact subordinate legislation, including the enactment of regulations by the federal, provincial, and territorial governments, and the enactment of bylaws by municipal governments.

Judicial

Delegated judicial functions are those powers that the federal, provincial, and territorial governments have given to the courts. A related function is commonly called **quasi-judicial**; a function that is essentially judicial in nature but which is exercised by an appointed official or an administrative tribunal.

Administrative

Delegated administrative functions, often called executive functions, are functions involving the application and enforcement of the legislation (for example, auditing responsibilities).

In addition, the powers delegated by the federal or provincial governments may be either **mandatory** or **discretionary** in nature. We may describe delegated powers that are mandatory in nature as **duties** imposed on the statutory delegate. The following is a delegation statement typical of various Boilers and Pressure Vessels Acts:

The Minister administers this Act but an accredited municipality and an accredited corporation shall provide for the administration of this Act in accordance with the order that designated it as an accredited municipality or corporation.

Mandatory powers may be recognized by the use of terminology such as “shall” and “must.” Discretionary powers, as the term suggests, allow statutory delegates to use their discretion in the exercise of their delegated powers. The Boilers and Pressure Vessels Act allows safety officers (inspectors) to exercise discretion and take actions they consider necessary to remove or reduce imminent serious dangers to persons or property regarding anything the Act applies to or due to a fire hazard or risk of explosion. Generally an Act has a paragraph that states:

If a safety officer (inspector) is, on reasonable and probable grounds, of the opinion that there is an imminent serious danger to persons or property because of any thing, process or activity to which this Act applies or because of a fire hazard or risk of an explosion, the officer may take any action that the officer considers necessary to remove or reduce the danger.

We identify discretionary powers by terms such as “may” or “discretion.”

Note: Some jurisdictions refer to Inspectors as Safety Officers. In this chapter, the term “Safety Officer” will be used to mean both “Safety Officer” and “Inspector.”



OBJECTIVE 3

Describe the authority that Safety Officers (Inspectors) have within their jurisdiction.

LIABILITY

Safety officers, acting reasonably and with probable grounds, may take any action deemed necessary to remove or reduce the danger. Thus, they have wide-ranging powers, which must be executed with care. An organization that has this responsibility also has the imposition of the neighbourhood principle referred to as a **duty of care**.

ELEMENTS OF LIABILITY FOR NEGLIGENCE

Three interlocking items are at the heart of any civil action. An analogy of a three-legged milking stool is often used to explain the interrelationship of these elements. Just as the stool will only stand with all three legs securely in place, a lawsuit balances on the same precarious structure. If all three elements are not in place in a lawsuit, it will not stand the scrutiny of the courts. The three elements are **duty of care**, **standard of care**, and **damages**.

Duty of Care

The defendant must have a duty to provide care to the plaintiff. The relationship between the parties may be situational, familial, or contractual, and it may be explicit or implied. Examples include the relationship between a lifeguard and a swimmer, a teacher and a child, an owner and a guest, a contractor and an owner, or a safety officer and a permit holder.

Standard of Care

The defendant, while in the relationship, must uphold a definable standard of care or performance with the plaintiff. This is often described as the **reasonable man principle**. In this principle, we compare the defendant's acts or omissions against a hypothetical reasonable individual who is always careful and prudent.

Consider a reasonable peer. What would this reasonable person (with similar training and experience) have done in a comparable situation? The comparison between our actions and what our peers would have done in the situation determines whether or not we met the standard of care.

Other items used to establish this standard of care may include training documents, procedure manuals, technical bulletins, codes, or other industry literature.

Damages

The third element is damage to the plaintiff. They must prove that damages (physical, emotional, or other) occurred. The damage must also have been a reasonably foreseeable result of the defendant's action or inaction which breached either the duty or standard of care.

If it can be established that

- a) the defendant owed a duty of care to the plaintiff,
- b) the defendant's performance was below their standard of care, and
- c) the plaintiff's damage occurred and should have been reasonably foreseeable to the defendant,

then the court will likely find the defendant negligent and liable for all or some of those damages.

BURDEN OF PROOF

The burden (or amount) of proof required to win in court is often described as proof “beyond reasonable doubt.”

While this is accurate when dealing with statute law, the burden of proof in civil law is much less demanding. In this setting, the party, defendant or plaintiff, who can show that the evidence proves the balance of probability of their case, will be successful. In very basic terms, if 51% or more of the evidence introduced proves the plaintiff’s claim, then they will be successful. The opposite is also true. This is why a civil action may appear to contradict the results of a criminal prosecution in the same matter.

Accordingly, the courts often determine the amount of the judgment (money to be paid) based upon the final balance of the evidence. If the plaintiff provides what is held to be 95% proof, they will likely be awarded a higher amount than if they can only prove 51%.

APPLICABILITY TO SAFETY OFFICERS (INSPECTORS)

A safety officer is expected to provide a service resulting in a reasonable level of safety, or to come to a reasonable conclusion about an incident. The authority provided to safety officers (inspectors) and their employers under a Boilers and Pressure Vessels Act establishes the duty of care. The standard of care is that of a reasonable safety officer with similar experience and training.

If a safety officer breaches the duty or standard of care, and a reasonable link can be established between that breach and the damages to the plaintiff, the court may hold both the safety officer and the employer liable for this negligence.

GOVERNMENTAL IMMUNITY

In the past, functions of government, which include inspections, have been immune from the questioning or scrutiny of the courts. The understanding was that the government (municipal, provincial, or federal) could only be the defendant in limited situations and often only if the government’s permission was received prior to initiating legal action. Our system has always held that, even though the government is responsible to the people, the electorate should only question government decisions at the ballot box. This distinction was not made in the area the law calls **gross negligence**, which is essentially very great negligence. Gross negligence has also been described as an almost wanton or willful disregard for obligations.

Recent court cases have modified this to make a distinction between policy decisions (whether inspections are done) and operational decisions (how often and how extensively inspections are done). This is the result of an increasing number of legal decisions. The general rule is that government makes policy decisions at the highest possible level (most often municipal councils or legislatures), while operational decisions are made in the field. Policy actions of the governing body are generally not subject to legal action; however, the courts will expose the actions of an organization to scrutiny.

The safety officer performs a function of government that has been delegated through the statute (Boilers and Pressure Vessels Act). Therefore, the same legal thinking applies to the actions of the safety officer.

GOOD FAITH

Good faith is a condition that the law expects all of us to meet in our interactions with others. In the case of the Boilers and Pressure Vessels Act, the expectation is that the individuals administering it will act with prudence, within their scope, and in accordance with their training and experience.



OBJECTIVE 4

Determine what are the offences and penalties under the Act and the appeal process.

PROHIBITIONS

A safety officer has the power to enforce the Boilers and Pressure Vessels Act by laying charges against someone who has not met their obligations under the legislation. This is often done when the recipient of an **order to comply** does not proceed as directed. Charges may also be laid to immediately penalize unsafe behavior under the scope of an Act. There is no requirement for an order to be issued first, although the fact that an order has been issued and ignored can be entered as evidence before a provincial court judge and may provide additional charges.

Offences include the following actions:

- interference
- false or misleading statements
- failure to keep records
- contravention of the Act or Regulations under the Act
- contravention of a condition in a permit, certificate, or variance
- contravention of an order
- failure to carry out an order within the time stated

A Boilers and Pressure Vessels Act may contain a statement such as this:

A person who interferes with or in any manner hinders a safety officer (inspector) in the exercise of his or her powers and duties under this Act is guilty of an offence.

This statement is self-explanatory. This is an offence against administrative law. It is an infringement of public rights and punishable under administrative laws.

Other statements that may be found in an Act, which are breaches of administrative law, include those given below:

A person who knowingly makes a false or misleading statement either orally or in writing is guilty of an offence.

A person who:

- contravenes this Act,
- contravenes a condition in a permit, certificate or variance,
- contravenes an order from a safety officer, or
- fails to carry out any action required in an order from a safety officer to be taken within the time specified in the order is guilty of an offence.

These statements outline what are commonly deemed to be offences under an Act.

PENALTIES

The Boilers and Pressure Vessels Act sets out the penalties that may be imposed on a person who is guilty of an offence under an Act. Each jurisdiction has set different penalties.

Typical penalty sections from a Boilers and Pressure Vessels Act contains statements such as the following:

A person who is guilty of an offence is liable

- (a) for a first offence,
 - (i) to a fine of not more than \$15,000 and, in the case of a continuing offence, to a further fine of not more than \$1,000 for each day during which the offence continues after the first day or part of a day, or
 - (ii) to imprisonment for a term not exceeding 6 months, or to both fines and imprisonment, and
- (b) for a second or subsequent offence,
 - (i) to a fine of not more than \$30,000 and, in the case of a continuing offence, to a further fine of not more than \$2,000 for each day or part of a day during which the offence continues after the first day, or
 - (ii) to imprisonment for a term not exceeding 12 months, or to both fines and imprisonment.

If a person is guilty of an offence under this Act, the court may, in addition to any other penalty imposed or order made, order the person to comply with this Act or any order, permit, certificate, or variance, or all or any one or more of them, as the case requires.

The wording of (a)(i) and (b)(i) could be a little confusing, but simply put for a first offence the penalty is a fine of not more than \$15,000 plus an additional \$1,000 per day (or part of a day) if the offence continues. For a second offence, the penalty is a fine of not more than \$30,000 plus an additional \$2,000 per day (or part of a day) if the offence continues.

APPEALS

As with all legislation, the Boilers and Pressure Vessels Act has an appeal process. A person who is served with an order may, if the person objects to the contents of the order, appeal to the chief inspector in charge of administering the Act.

If dissatisfied with the decision received from the chief inspector, he or she may proceed further and appeal the order to an appointed technical council. The decision of this technical council is final on all technical matters.

A person who has been served with an order has a statutory right to continue to appeal to the Court of Queen's Bench. However, a person may do so only on a question of law or jurisdiction and not on technical matters.



OBJECTIVE 5

Describe the typical Regulations under the Boilers and Pressure Vessels Act.

REGULATIONS AND THEIR SOURCE

Regulations are a form of law, often referred to as **delegated** or **subordinate** legislation. Like Acts, Regulations have the same binding legal effect and usually state rules that apply generally, rather than to specific persons or things. However, regulations are not made by the legislature. Rather, they are made by persons or bodies to whom the legislature has delegated authority, such as the governor-in-council (the lieutenant-governor acting on the advice of cabinet), a minister, or an administrative body or agency. Authority to make regulations must be expressly delegated by an Act. Acts that authorize the making of regulations are called **Enabling Acts**. The Boilers and Pressure Vessels Act is an Enabling Act.

The Boilers and Pressure Vessels Act may set out the framework of a regulatory scheme and delegate the authority to develop the details and express them in regulations. Alternatively, a Boilers and Pressure Vessels Act may do little more than delegate authority, leaving the substance of the scheme to be dealt with in regulations.

PURPOSE OF GOVERNMENT REGULATION

Regulations are a form of government intervention in the economy. While there are costs associated with regulation, there are also benefits accruing from regulation. For example, setting safety standards for nuclear power stations may impose costs on the operators, but it also helps to minimize the risk of radioactive pollution. The job of regulators, then, is to weigh the advantages and disadvantages of every viable response to a situation that merits government intervention and to recommend regulation when it is the best alternative. This involves balancing a number of priorities such as public health and safety, environmental protection and sustainable development, or economic efficiency and performance.

THE LEGAL FRAMEWORK FOR REGULATIONS

A delegate granted regulation-making authority does not have a free hand in making regulations. There are a number of legal constraints on the delegate's power including the Constitution, in particular, the Canadian Charter of Rights and Freedoms.

Delegates must also stay within the scope of the Act that delegates the regulation-making authority (the Enabling Act) and must not conflict with it or restrict or extend the scope of its application.

DRIVERS OF REGULATIONS

Ideas for regulations come mainly from public servants who administer regulatory schemes, and from members of the public (stakeholders) who are regulated by those schemes. Ideas frequently result from public consultation conducted by public servants. Of course, they may also come from the general public, ministers, other members of the legislature, the courts, and administrative agencies.

TYPICAL REGULATIONS UNDER A BOILERS AND PRESSURE VESSELS ACT

Boiler and Pressure Vessels Regulations

This regulation sets out

- the definitions of the limits of what is regulated;
- the requirements for registration of the design for a boiler, pressure vessel, fitting or pressure piping system; and
- the inspection/certification permit requirements and the posting of the permit.

Design, Construction, and Installation of Boilers and Pressure Vessels Regulations

This regulation details the requirements for

- the registration of a boiler, pressure vessel, and pressure piping system design;
- the registration of a fitting design;
- the registration of a welding procedure;
- the requirements to be met prior to and during construction; and
- the requirements for continuing inspections by a safety officer.

Power Engineer Regulations

This regulation sets out

- supervision levels for power plants and heating plants;
- authorization to supervise;
- requirements for a log-book;
- certification requirements and issuance; and
- certificate examination requirements.

Pressure Welder's Regulations

This regulation details the types of welder's certificates, the certificate examination requirements, and the performance qualification tests.



OBJECTIVE 6

Describe the typical Codes and Standards referenced by the Boilers and Pressure Vessels Act.

ADOPTION OF CODES AND RULES

The Boilers and Pressure Vessels Act or the Regulations under the Act include a statement such as

The following codes and standards, as amended from time to time, are declared to be in force in respect of pressure equipment.

This statement is typically followed by a listing of various codes and standards:

- (a) CSA B51 - Boiler, Pressure Vessel, and Pressure Piping Code
- (b) CSA B52 - Mechanical Refrigeration Code
- (c) ASME Boiler and Pressure Vessel Code
- (d) ASME B31.1 - Power Piping
- (e) ASME B31.3 - Process Piping
- (f) ASME B31.5 - Refrigeration Piping
- (g) MSS SP 25 - Standard Marking System for Valves, Fittings, Flanges and Unions
- (h) ANSI/NB-23 - National Board Inspection Code

To include additions to the code, the Act or Regulation would also include a statement such as this:

Any addenda to the codes or bodies of rules specified above and any rulings or cases issued by the American Society of Mechanical Engineers (ASME) shall be deemed to be adopted upon their publication.

This statement insures that the Act is always current with respect to any changes to the codes and standards.

The following is a very brief review of some of the codes listed above.

CSA B51 - Boiler, Pressure Vessel, and Pressure Piping Code and CSA B52 - Mechanical Refrigeration Code

These codes are very familiar to Power Engineers studying for the Second Class Certificate and have been covered and explained in previous courses.

ASME BPVC (Boiler and Pressure Vessel Code)

The ASME BPVC (Boiler and Pressure Vessel Code) is a collection of twelve codes published by the ASME Boiler and Pressure Vessel Code Committee. Of these sections, the following are of greatest interest to Power Engineers.

Section I: Power Boilers, and **Section VII: Recommended Guidelines for the Care of Power Boilers** are very familiar to Power Engineers. ASME Section I provides requirements for construction of power boilers, including high pressure steam boilers, high temperature water boilers, heat recovery steam generators, locomotive and traction engine boilers, electric boilers, miniature boilers, and certain fired pressure vessels used in stationary service. ASME VII provides guidelines for operating, maintaining, and inspecting power boilers (except for locomotive boilers, high-temperature water boilers, nuclear power-plant boilers, and marine boilers). It also has guidelines for operation of auxiliary equipment and appliances that affect safe and reliable power boiler operation.

Section IV: Heating Boilers and **Section VI: Recommended Guidelines for the Care and Operation of Heating Boilers** are also very familiar to Power Engineers. ASME IV contains the requirements for design, fabrication, installation and inspection of directly-fired steam heating, hot water heating, hot water supply boilers, and potable water heaters intended for low pressure service. ASME VI provides guidelines for the operation of steel and cast-iron boilers designed to ASME IV, including their associated controls and fuel-burning equipment.

Section II: Materials and Specifications. Since the introduction of the ASME Codes, materials used in the construction of boilers and pressure vessels have been tested and approved for use under specific operating conditions and with specific process fluids.

Section II is made up of four parts:

Part A Ferrous Material Specifications: used for pipe, tubes, fittings, plate, and castings.

Part B Non-ferrous Material Specifications: such as aluminum, copper, nickel, titanium, and zirconium and their alloys used for pipe, tubes, fittings, plate and castings.

Part C Specifications for Welding Rods, Electrodes, and Filler Metals: Because welding plays an important role in the construction of pressure equipment, the ASME BPVC provides a list of acceptable welding and brazing materials.

Part D Properties: ASME II-D contains three subparts:

Subpart 1: Stress Tables

This section contains stress tables of permissible construction materials.

Subpart 2: Physical Properties Tables

This section has physical property tables for most of the alloys used in Code construction. These cover thermal expansion (instantaneous, mean, and linear), thermal conductivity, thermal diffusivity, and modulus of elasticity, as a function of temperature. Subpart 2 also contains tables of density and Poisson's ratio for ferrous and nonferrous alloys

Subpart 3: Charts and Tables for Determining Shell Thickness of Components Under External Pressure

This section contains charts and tables for determining thickness of components under external pressure, such as firetubes, furnace tubes, and flues.

Section V: Non-Destructive Examination: This code addresses the NDE test methods and requirements referenced by other sections of the ASME BPVC, such as ASME-I and ASME-VIII. These Codes have specific NDE requirements and acceptance criteria for the referenced test methods. Power Engineers must be aware of the relationship between ASME-V and other sections, and must be able to determine which Code contains the relevant examination acceptance criteria.



Section V includes the following articles:

- Article 1:** Contains requirements and methods of NDE that are code requirements to the extent that they are specifically referenced by other code sections.
- Article 2:** Covers the radiographic test method used for the examination of materials.
- Article 4:** Covers ultrasonic examination requirements of welds.
- Article 5:** Provides requirements for selecting and developing ultrasonic thickness determination and ultrasonic examination procedures.
- Article 6:** Describes the methodology and techniques used for liquid-penetrant examination.
- Article 7:** Describes the requirements and methodology used to perform magnetic-particle examination.
- Article 8:** Describes the techniques used when performing eddy current examinations on conductive-nonferromagnetic and coated ferritic materials.
- Article 9:** Details several techniques used for visual examination: direct viewing, remote viewing, and translucent examination.
- Article 10:** Describes methods and requirements for performing leak testing.
- Articles 11 - 13:** Address acoustic emission examination methods and procedures

Section VIII: Rules for Construction of Pressure Vessels. This Section is divided into three separate Divisions:

- **Division 1**
- **Division 2 - Alternative Rules**
- **Division 3 - Alternative Rules for Construction of High Pressure Vessels.**

These codes are for the construction of new pressure vessels. Many of the design rules are identical in VIII-1 and VIII-2. VIII-3 provides requirements for the design, fabrication, inspection, testing, and certification of fired and unfired pressure vessels operating at pressures generally above 68.9 MPa

The rules in VIII-1 do not cover all applications and configurations. When design rules are not available, Paragraph U-2(g) permits the design engineer to design components. Paragraph UG-101 allows proof testing to determine the maximum allowable working pressure for a component. Section VIII-2 does not include a rule similar to UG-101 since VIII-2 permits design by analysis. VIII-2 requires that all longitudinal and circumferential butt joints must be radiographed. VIII-1 permits various levels of welded-joint examination. The degree of weld examination influences the required vessel thickness through the use of joint efficiency factors, referred to as E (used in code calculations). A joint efficiency factor of 1.0 corresponds to a safety factor of 3.5. A joint efficiency factor of 0.7 corresponds to a safety factor of 5 and results in a 43% increase in the required vessel wall thickness.

Section IX: Welding, Brazing, and Fusing Qualifications. This Code contains rules for the qualification of the welding, brazing, and fusing procedures required by other BPVC Sections. It also covers the qualification and requalification of welders, brazers, and welding/brazing operators, to permit them to perform welding or brazing on Code-compliant vessels.

ASME Section IX has four parts: QG, QW, QB, and QF.

Part QG covers General Requirements. A thorough understanding of this Part is essential for understanding the other parts of ASME-IX. The content covered in Part QG include a general treatment of weld procedure qualification, procedure qualification records, and welder performance qualification. Essential, nonessential, and supplementary essential weld variables are also described. QG-109.2 includes an extensive glossary of terms used in ASME-IX.

Part QW covers the preparation of Welding Procedure Specifications (WPS) and the qualification of welding procedures, welders, and welding operators for all types of manual and machine welding processes. Of all the Parts of Section IX, Part QW may be of greatest significance to Power Engineers. It is organized into five Articles:

- Article I Welding General Requirements
- Article II Welding Procedure Qualifications
- Article III Welding Performance Qualifications
- Article IV Welding Data
- Article V Standard Welding Procedure Specifications

The welding processes covered in Part QW include:

- oxyfuel welding (OFW)
- shielded metal arc welding (SMAW)
- submerged arc welding (SAW)
- gas metal arc welding (GMAW)
- gas tungsten-arc welding (GTAW)
- plasma arc welding (PAW)
- electroslag welding (ESW)
- electrogas welding (EGW)
- electron beam welding (EBW)
- laser beam welding (LBW)
- diffusion welding (DFW)
- friction stir welding (FSW)
- flash welding
- stud welding
- inertia and continuous drive friction welding
- resistance spot and projection welding

Part QB covers the preparation of brazing procedure specifications, and the qualification of brazing procedures, brazers, and brazing operators. It is organized into four Articles:

- Article XI Brazing General Requirements
- Article XII Brazing Procedure Qualifications
- Article XIII Brazing Performance Qualifications
- Article XIV Brazing Data

Part QF covers Plastic Fusing, the preparation and qualification of fusing procedure specifications (FPS), and the performance qualification of fusing machine operators.



ASME B31.1 Power Piping

ASME B31.1 is not part of the ASME BPVC, despite containing important design information about boiler external piping (BEP) and non-boiler external piping (NBEP). Rather, it is one of eight Codes that comprise the **ASME B31 Code for Pressure Piping**.

ASME B31.1 was written to cover piping used for steam and water systems in power plants and utility heating systems. It includes the piping and equipment used for boiler fuel gas and fuel oil systems within the plant proper (i.e. downstream of the supplier's metering station.) The code provides minimum requirements for safety in the design of new piping, and provides guidance in the repair, replacement, and modification of existing piping systems.

Some of the contents of ASME B31.1 originated in the ASME BPVC. For this reason, there may appear to be overlapping jurisdiction, and confusion over which of the two design codes to use. For this reason, ASME B31.1 Figures 100.1.2(A.1), 100.1.2(A.2), 100.1.2(B), and 100.1.2(C) outline the administrative jurisdiction and technical responsibility of the ASME BPVC and B31.1. Similar illustrations are found in ASME BPVC Section I. These are Figures PG-58.3.1(a), PG-58.3.1(b), PG-58.3.1(c), PG-58.3.2, and PG-58.3.3.

Boiler external piping design is covered in Part 6, Paragraph 122.1. This paragraph includes very specific design requirements, including pressure-temperature relationships, valving, valve design criteria, and accepted materials, for the following boiler piping systems:

- steam piping (122.1.2)
- feedwater piping (122.1.3)
- blowoff and blowdown piping (122.1.4)
- boiler drains (122.1.5)

Paragraph 122.2 has the design requirements for other piping systems:

- blowoff and blowdown piping in non-boiler external piping (122.2)
- instrument, control, and sampling piping (122.3)
- spray-type desuperheater piping for use on steam generators and reheat piping (122.4)
- pressure reducing valves (122.5)
- pressure relief piping (122.6)
- piping for flammable or combustible liquids (122.7)
- piping for flammable gases, toxic fluids, or nonflammable nontoxic gases (122.8)
- piping for corrosive liquids and gases (122.9)
- temporary piping systems (122.10)
- steam trap piping (122.11)
- exhaust and pump suction piping (122.12)
- pump discharge piping (122.13)
- district heating and steam distribution systems (122.14)

Some of the other areas covered by ASME B31.1 are allowable stress for thermal expansion and flexibility analysis of a piping system. This includes calculations of the cold spring in the piping system. Piping Supports and Restraints requirements are provided in Sections 120 and 121.

ASME B31.3 Process Piping

ASME B31.3 is another volume of the ASME B31 Pressure Piping Code. The scope of this code is very broad since it covers the scope of process piping found in industrial plants, such as petrochemical, chemical, pharmaceutical, textile, paper, semiconductor, and cryogenic plants. The code allows the owner to select the piping code most appropriate to the piping installation. It is intended to cover piping for all fluids, including:

- raw, intermediate, and finished chemicals
- petroleum products
- gas, steam, air, and water
- fluidized solids
- refrigerants
- cryogenic fluids

The code was originally intended to cover all piping within a process plant. The code now states that it is the owners' responsibility to decide which code is most applicable to their piping system.

The basic intent of the code is stated in the following paragraphs from ASME B31.3:

- 300(c)(3)** The Code generally employs a simplified approach for many of its requirements. A designer capable of applying a more complete and rigorous analysis ... shall have the latitude of applying such analysis in the development of designs and fabrications. The designer shall provide details of design, construction, examination, and testing, along with calculations consistent with the design criteria of this Code. The details shall be documented in the engineering design and their validity accepted by the owner.
- 300(c)(4)** Piping elements should, insofar as practicable, conform to the specifications and standards listed in this Code. Piping elements neither specifically approved nor specifically prohibited by this code may be used provided they are qualified for use as set forth in applicable chapters of this Code.
- 300(c)(5)** The engineering design shall specify any unusual requirements for a particular service. Where service requirements necessitate measures beyond those required by this Code, such measures shall be specified by the engineering design. Where so specified the code requires that they be accomplished.

These statements help to understand the philosophy of the ASME B31.3 Code. The code is not intended to set procedures, approve every component, or approve every material used. Rather, procedures are set for use of unlisted components and unlisted materials. This code gives great freedom to the designer, but the designer must be able to demonstrate (to the owner) that the design is valid.

The code consists of nine chapters. The first six are called the **base code** and provide the basic piping code requirements for normal and Category D fluid service metallic piping. Category D fluid service includes fluids that are non-toxic, non-flammable, and not dangerous to human tissue, less than 1035 kPa, and range from -29°C to 186°C.

Chapter VII contains rules for non-metallic piping and additional requirements for metallic piping lined with non-metals.

Chapter VIII contains rules for piping conveying Category M fluids. These fluids are so highly toxic that a single exposure to a very small quantity of leaked fluid can produce serious irreversible harm to persons on breathing or bodily contact, even when prompt restorative measures are taken.



Chapter IX contains rules for high-pressure piping. This Chapter considers “high pressure” to be in excess of that allowed by the ASME B16.5 Class 2500 rating for the specified design temperature and material group (roughly in excess of 43 MPa, depending on the material and service temperature).

ASME B31.3 refers to the concept of **safeguarding**, which is covered in **B31.3 Appendix G**. Safeguarding is the provision of protective measures to minimize the risk of accidental piping damage, or to minimize the harmful consequences of potential piping failure. In most instances, facilities have adequate inherent safeguarding, including provision for expansion, drainage, isolation, thrust blocks, and pressure relief devices. However, in some instances, additional engineered safeguards are necessary.

Safeguarding involves consideration of factors beyond the simple design of the pipe in the overall safety of the piping installation. These considerations may include:

- the hazardous properties of the fluid, under severe temperature and pressure conditions
- the quantity of fluid that could be released by a piping failure, with special consideration to the fluid toxicity
- ambient and surface temperature extremes
- damage from vehicular traffic or other actions of operating and maintenance personnel
- the development of dangerous static charges, and the need for grounding systems.

Safeguarding addresses the consequences of failure and probable sources of damage, which are risks associated with a piping installation.

ANSI/NB-23 National Board Inspection Code

The purpose of the National Board Inspection Code (NBIC) is to maintain the integrity of pressure-retaining items after they have been placed into service. This is done by providing rules for inspection, repair, and alteration of pressure equipment, thereby ensuring on-going safe operation.

The NBIC is intended to provide guidance to inspectors, jurisdictions, installers, contractors, and organizations performing repairs and alterations, thereby encouraging the uniform administration of rules pertaining to pressure-retaining items.

Though it provides guidance for the process of inspection, repair, and alteration, the NBIC does not provide details for all conditions found in pressure-retaining items. Where complete details are not provided in the NBIC, the user is advised to seek guidance from the Jurisdiction or other credible technical sources.

The National Board Inspection Code (NBIC) is issued every two years. It is organized into four parts:

- **Part 1, Installation.** This Part provides requirements and guidance to ensure pressure-retaining items are installed and function properly. Proper installations meet the specific safety criteria for construction, materials, design, supports, safety devices, operation, testing, and maintenance outlined in this Part of the Code.
- **Part 2, Inspection.** This Part contains information and guidance for performing and documenting inspections of all types of pressure-retaining items. It includes information on personnel safety, non-destructive examination, tests, failure mechanisms, types of pressure equipment, fitness for service, risk-based assessments, and performance-based standards.
- **Part 3, Repairs and Alterations.** This Part provides information and guidance to perform, verify, and document acceptable repairs of, or alterations to, pressure-retaining items, regardless of code of construction. It also provides alternative methods for examination, testing, and heat treatment if the original construction code requirements cannot be met. Specific acceptable and proven repair methods are also provided.
- **Part 4, Pressure Relief Devices.** This Part provides information and guidance to perform, verify, and document the installation, inspection, and repair of pressure relief devices. It has a supplemental section with specialized information, such as pressure margins, recommended repair practices, and test stand design details.



CHAPTER QUESTIONS

1.
 - a) In your own words, briefly describe constitutional law.
 - b) Where is the constitutional authority found for your jurisdiction to create municipal institutions?
 - c) Where is the authority for municipal governments found?
 - d) State two unique characteristics of our Constitution.
2.
 - a) What are the three primary classifications of courts in Canada?
 - b) Why is the jurisdiction of the Court of Queen's Bench of interest to the safety officer?
3.
 - a) In your own words define "statutory delegate."
 - b) State the difference between "mandatory" and "discretionary" powers.
 - c) What are the three types of functions Governments may delegate?
 - d) In your own words describe "standard of care" as applicable to a safety officer.
4.
 - a) Is there a legal responsibility for Power Engineers to retain a log book? Explain your answer.
 - b) If a Power Engineer knowingly makes a false statement concerning matters under the Boilers and Pressure Vessels Act, describe the penalty allowed.
5. A new piping system which is part of the boiler external piping is to be examined. Explain, in your own words, who is required to inspect this piping system, and under what code requirements.





Plant Design and Installation

LEARNING OUTCOME

When you complete this chapter you should be able to:

Explain the codes and procedures involved in the design and construction of a new plant.

LEARNING OBJECTIVES

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

- 1. State the codes and standards that must be followed when designing and building a new plant.*
- 2. Describe the steps involved in developing specifications and contracts for new installations and modifications.*
- 3. Explain the major steps involved in the design and construction of a new plant.*
- 4. Explain the roles and responsibilities in the design and construction of a new plant.*
- 5. Explain how the design and construction of a new plant are administered and controlled.*



OBJECTIVE 1

State the codes and standards that must be followed when designing and building a new plant.

When a new plant is designed and built, the codes and standards for the location of the new plant must be followed. A plant installed in Canada must be built to standards and codes used by the province. For example, an oil sands plant installed in Alberta must meet all of the standards and codes adopted in Alberta.

Because the codes are updated regularly, the newest version of the codes must be used. Each engineering discipline has codes and standards that must be followed. Engineering disciplines include: environmental (includes water and air), civil, chemical, mechanical, and electrical.

Provincial jurisdictions also require companies to obtain work permits before work on buildings or facilities commence. These permits fall under the electrical codes, plumbing codes, building codes, fire codes, and gas codes. Other standards that must be adhered to are environmental, air, water and wastewater, and transportation.

Local standards involve such items as traffic, noise, odour, and appearance.

Benefits of obtaining a permit are that the installation conforms to construction and safety standards accepted under the Safety Codes Act, and certified codes officers do inspections.

With regard to steam and pressure plant legislation, the following codes and standards are typically referenced:

- Canadian Standards Association B51, Boiler, Pressure Vessel, and Pressure Piping Code
 - Part 1, Boiler, Pressure Vessel, and Pressure Piping Code including Appendix I Automotive Propane Vessel Standards
 - Part 2, High-Pressure Cylinders for the Onboard Storage of Natural Gas as a Fuel for Automotive Vehicles
 - Part 3, Requirements for Compressed Natural Gas (CNG) Refuelling Station Pressure Piping Systems and Ground Storage Vessels
- CSA B52, Mechanical Refrigeration Code
- CSA Z662, Oil and Gas Pipeline Systems

American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, The ASME Codes are extensively used by Power Engineers, because they apply to power boilers, pressure vessels, and pressure piping.

- Section I, Rules for Construction of Power Boilers
- Section II Materials
 - Part A – Ferrous Material Specifications
 - Part B – Nonferrous Material Specifications
 - Part C – Specifications for Welding Rods, Electrodes, and Filler Metals
 - Part D – Properties
- Section IV - Rules for Construction of Heating Boilers
- Section V - Nondestructive Examination
- Section VI- Recommended Rules for the Care and Operation of Heating Boilers
- Section VII - Recommended Guidelines for the care of Power Boilers

- Section VIII - Rules for Construction of Pressure Vessels
- Section IX - Welding, Brazing, and Fusing Qualifications
- ASME B31.1 - Power Piping
- ASME B31.3 - Process Piping
- ASME B31.4 - Pipeline Transportation Systems for Liquids and Slurries
- ASME B31.5 - Refrigeration Piping and Heat Transfer Components
- CGA-G2.1 - Requirements for the Storage and Handling of Anhydrous Ammonia
- National Fire Protection Association NFPA 58, Liquefied Petroleum Gas Code
- Manufacturers Standardization Society of the Valve and Fittings Industry, MSS SP-25 Standard Marking System for Valves, Fittings, Flanges, and Unions
- TEMA - Standards of Tubular Exchanger Manufacturers Association

The standards developed by the various organizations become a base for the codes in order to determine the quality of the material and the workmanship.

Research and Testing Organizations

- ASTM - The American Society for Testing and Materials
- NFPA - National Fire Protection Association
- UL - Underwriters' Laboratories
- FM - Factory Mutual
- ANSI - The American National Standards Institute

Professional Associations

- ASHRAE - The American Society of Heating, Refrigerating and Air Conditioning Engineers
- ASCE - The American Society of Civil Engineers
- ASME - The American Society of Mechanical Engineers

Trade Associations

- APA - The American Plywood Association
- SMACNA - Sheet Metal and Air Conditioning Contractors' National Association
- ACI - American Concrete Institute



OBJECTIVE 2

Describe the steps involved in developing specifications and contracts for new installations and modifications.

FEASIBILITY STUDIES

Before an industrial plant can be constructed, an engineering or feasibility study must be completed to evaluate the feasibility of the plant. The study is used to determine the plant size and to estimate costs. The company building the plant may have a large enough engineering staff to complete the study itself, or it may be contracted to an engineering company. A separate engineering company does the detailed engineering. Detailed engineering has the information and specifications required to construct the plant.

The primary emphasis of the engineering feasibility study is economics. The study is used to determine the cost of the new plant and to ascertain its economic viability – whether the plant can make a profit. If the plant design appears profitable, the study is used to obtain capital funds to build the plant. The study includes the cost of building the plant as well as other related costs such as operation of the plant, maintenance, depreciation, insurance, interest, and taxes. With this information, an operating and maintenance budget for the proposed plant is developed.

The feasibility study must also address other issues that will affect the viability of building and operating a new plant, and which also impact the cost of construction and operation. These include the following:

- Potential for air, water, and ground pollution, and the need for monitoring and mitigating equipment
- Potential for unacceptable levels of noise, and the need for monitoring and mitigating equipment
- Local regulations and bylaws which need to be complied with

Detailed Design and Specifications

After a new plant site is selected and the various government approvals are obtained, the design of the plant is finalized. Usually, the general plant design and physical size are required to get the approvals.

Detailed design follows the acceptance of the feasibility study, funding, and procurement of permits. There are different priorities at each plant, but some of the basic choices that have to be made are:

- Type of fuel used
- The production process used
- Amount of auxiliary equipment
- The types of instrumentation and control
- Power supply

The engineering company contracted to design the plant finalizes the design of the plant. Plot plans for the plant site, including roads, buildings, process units, and offsite facilities are produced. The engineering company completes the design drawings that tie the process units together. The engineering company produces drawings and specifications, with the amount of detail required for construction companies to create competitive bids.

The larger process areas of the plant are often purchased as standard or proven designs. For example, a new power plant may have a steam generator supplied by Babcock and Wilcox and a turbine supplied by Hitachi. These are proven designs that have been used in other plants. Babcock and Wilcox supplies the detailed drawings and specification sheets for the steam generator and its associated equipment. Hitachi supplies the drawings and specifications for the turbine and electric generator and associated equipment. The engineering company completes the engineering required to attach the equipment supplied by the main vendors. This engineering includes such things as interconnecting piping, electrical systems and instrumentation.

The plant owner stays involved during the design process. Any additions or options the owner specifies are incorporated into the design. It is cost effective to incorporate changes to the design at the design stage, rather than after construction has commenced.

Drawings and Specifications

Drawings and specifications are necessary to obtain bids for construction, to supervise the purchasing, and for construction of the plant. The drawings are a graphic representation of the plant, while the specification sheets provide details of the components of the plant. The drawings include the location of the equipment including interconnecting piping and wiring. Between the two, the work to be done is clearly defined. The specifications should include the details of each item shown on the drawings. Specifications are intended to be very detailed although they also include some general stipulations and conditions relating to the work as a whole.

For example, in a piping system for an industrial plant, the drawings show the piping layout including detailed dimensions. The piping drawings also refer to the piping specifications. This is done with a piping specification number. The Piping and Instrumentation Diagram (P&ID) in Figure 1 contains piping line numbers. Refer to the specification number to obtain details for the piping. The specifications for the piping lists all of the design requirements including:

- Design pressure and temperature
- Operating temperature and pressure
- Grade designation or the schedule of the pipe fittings and valves
- Type and pressure ratings of the joints including any special requirements
- Quality of materials including inspection and acceptance requirements
- Instrumentation including control valves

Developing Drawings and Specifications

The engineering company produces preliminary drawings that contain enough detail to do the feasibility study of the plant but not enough detail to construct the facility. Drawings included in the feasibility study are Process Flow Diagrams (PFDs) of the overall plant process streams. There are also plot plans showing all roads, buildings, offsite facilities, and storage facilities. At this stage a preliminary set of Process Flow Diagrams has been created.

The design specifications and the isometric or Computer Assisted Drafting (CAD) drawings are done after the feasibility study has been completed. This is the detailed design stage. At this stage, the drawings and plot plans have complete details and refer to the design specifications. The specifications must also contain all the details needed for purchasing materials and for plant construction.

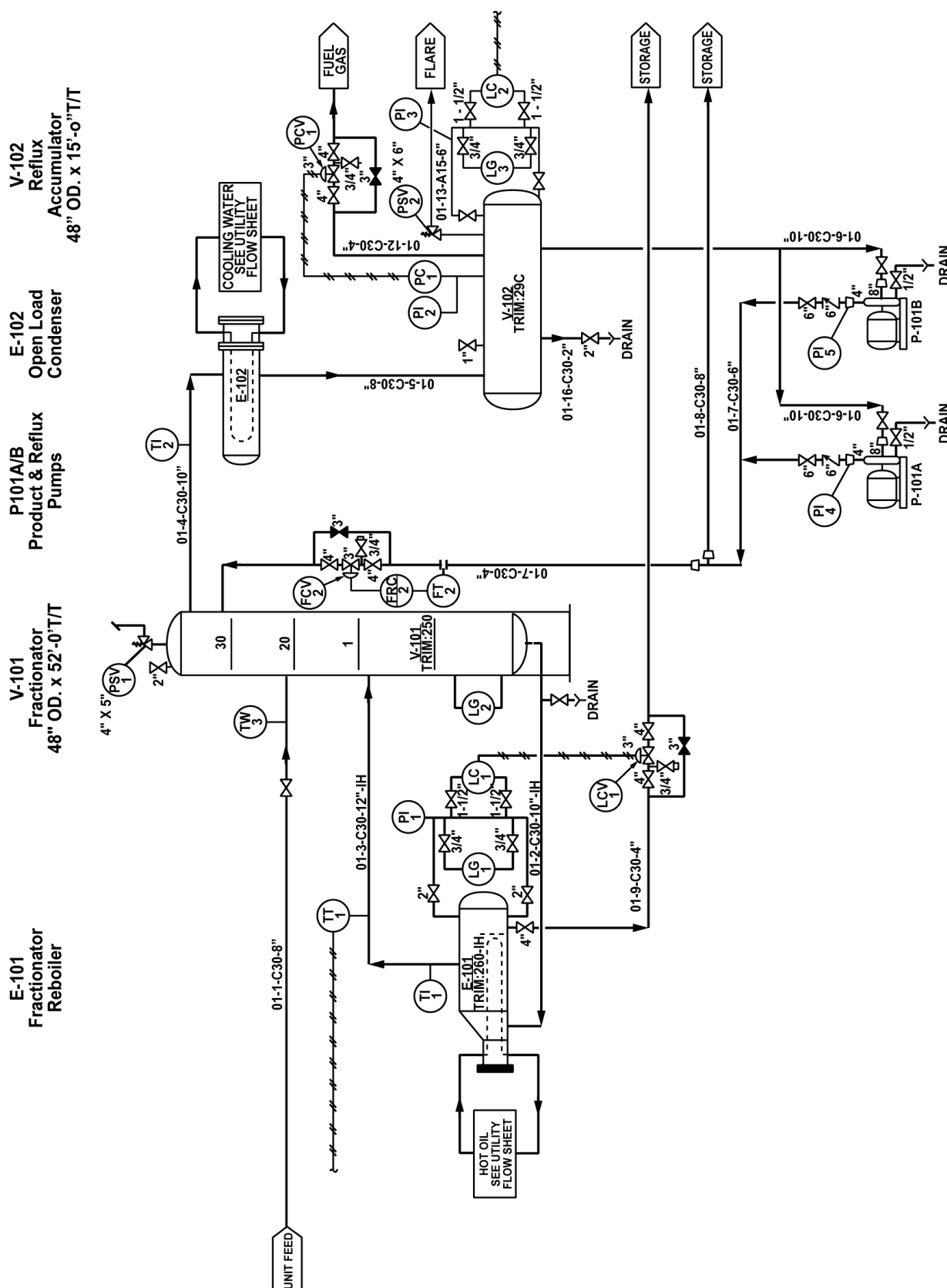
Plant Modifications

When a plant adds new equipment, the existing specifications are used if possible. For example, if a new feedwater pump is added to an existing system, the P&ID drawings are modified to include the additional piping. The piping specifications listed on the P&ID refer to the existing specifications. When new piping is added with different specifications from the existing piping, the specifications sheets have to be updated. This happens if the new system uses different material, is a different size, or has different pressure or temperature ratings.

If a new unit (boiler or process train) is added to an existing plant, it will have its own set of drawings and specifications. Existing specifications can only be used when the new unit is similar to existing units.



Figure 1 – Piping and Instrumentation Diagram



OBJECTIVE 3

Explain the major steps involved in the design and construction of a new plant.

PLANT DESIGN

The design of a new plant goes through several phases, even before the detailed engineering begins. The first step is the feasibility study used to decide whether the plant is economically feasible. Once through the feasibility phase, the engineering proceeds to the detailed design which produces the drawings and specifications needed to purchase materials for construction.

Engineering Study

This phase is also called a feasibility study. In its basic form, it is used to determine whether the plant should be constructed and if the plant makes economic sense for the corporate or government owner. The study can be carried out by the purchasing company's engineering staff or by a contracted engineering company. Some of the things decided in the study are:

- Size of the plant and its main process flows
- Demand for product. For example the product may be electrical power, oil and gas, or chemicals
- The influence of government regulations such as environmental impacts
- Economic alternatives such as different process designs or plant sizes
- Choices of plant processes, fuels, auxiliary equipment, degree of instrumentation and automatic control.
- Mode of operation – whether the plant is run in a steady state mode, is base loaded or used for peak loads
- Choice of cycle – it may be a simple cycle or include such things as cogeneration
- Choice of fuel – the cost and availability of the fuel, handling costs, and fixed charges are included
- Amount of instrumentation and automatic control. More automation usually means fewer personnel and higher efficiency. Most new installations incorporate computer control with a distributed control system or a field bus network.

The engineering study includes a report used to obtain capital funds for plant construction. It includes outlays for such items as operations, maintenance, depreciation, insurance, interest, taxes, and a budget. It includes recommendations for such items as:

- Capital required
- Operating costs
- Fixed costs

The engineering study often includes economic alternatives. Such alternatives could include different plant locations, various plant output sizes, or use of different fuels.



Detailed Design

The detailed design process follows the engineering study and the decision to proceed.

The detailed design builds upon the work accomplished in the engineering study but contains much more detail. Items included in the detailed design include:

- Detailed drawings such as P&IDs
- Detailed specifications for all engineering disciplines including material specifications
- Construction drawings including isometric piping drawings
- Process flow diagrams with mass balances

Drawings and Specifications

As the engineering continues, all of the information is summarized in drawings and specifications. The design drawings may be paper-based, or computer-based on CAD programs, or a combination of the two. The design may also include the construction of a scale model of the plant equipment. The model is useful to determine placement of equipment, location of pipe on pipe racks and to train plant personnel. Any interference with beams or ladders can be easily detected. Three-dimensional (3-D) computer images of the equipment are generated. This eliminates the need for an actual scale model. The detailed design drawings and specifications include all details needed to construct the plant. Details included are:

- Piping
- Electrical
- Civil such as buildings, steelwork, roads and underground piping
- Instrumentation and control systems

Performance Specifications

Performance specifications are used for specifying outputs of pumps, fans, turbines, motors, and electric generators. For example, the desired output of a pump is given to a pump manufacturer. The manufacturer or vendor then supplies a pump capable of meeting the output at the design conditions. Because manufacturers have specialized experience they choose the model best suited for the application. Pump performance is checked during the performance run of the plant.

PLANT CONSTRUCTION

The plant construction also goes through several phases. A construction company or primary or general contractor must be selected. Once selected, the primary contractor oversees the construction of the plant. Once the plant is constructed, the equipment is started up (or commissioned).

Bidding or Negotiation Phase

The bidding phase follows the detailed design phase. Companies with the expertise to construct the plant are located. A short list of the most suitable companies is compiled. This list may be one to six companies, and a copy of the plant design is given to each one. Each company supplies a bid based upon the plant design. The bid documents detail the timeline, forms of payment, and all other required details. After the bids are received, a bid review process analyses the competing bids. From this analysis the winning bid is selected. It is usually the bid with the lowest cost. In some cases, the lowest cost bid includes some other consideration or requirement which is not acceptable, in which case another bid may be accepted instead.

Construction Phase

After a successful bid is accepted for the construction of the plant, work at the site can commence. During the construction phase, the engineering staff changes its focus to contract administration and quality assurance. Contract administration includes resolving any design changes. These may be a result of omissions from, or factors that do not comply with, the original design. They may also be changes requested by the plant owners. Change orders add to the cost of the project, as the changes must be re-engineered and changes made to the drawings and specifications. Smaller field changes require little or no engineering changes.

The construction takes place with many trades working on the project simultaneously. The basic order of the work is listed below.

- Site grading and roads
- Excavating for underground piping and foundations
- Laying underground piping and pouring cement foundations
- Work on the main electrical supply including installation of the main substation and motor control centres
- Placing of major pieces of equipment on their foundations
- Installing steelwork for buildings and structures
- Erection of larger buildings and furnaces
- Placing of large pressure vessels and rotating machines on their foundations
- Installation of large diameter piping
- Installation of small diameter piping, including instrumentation and electrical wiring
- Installation of small pumps, motors and turbines
- Insulation of piping and tanks

Pre-commissioning

Pre-commissioning begins once the piping is complete. It includes steps that have to be completed before the commissioning or startup of the plant can begin. Activities included in the pre-commissioning schedule include:

- Air or steam blowing and purging of piping to remove debris, scales, and liquids; often preceded by a chemical clean
- Checking the operation of control loops from the control room to field devices such as valves and dampers.
- Hydrostatic testing and leak testing of flanges and piping
- Test running pumps and motors

After the pre-commissioning steps are complete, the plant startup can begin.



Commissioning

Commissioning is the term used to describe the process startup of a new plant. The commissioning is done in systems, starting with the plant offsites and utilities and working through the process, until the final product is produced. It is critical to go slowly, following the manufacturers recommendations. Limits on temperatures and pressures must be closely adhered to. The steps differ for different types of plants. A sample order of systems startup is listed below.

- Instrument and plant air systems
- Water and nitrogen purge systems
- Cooling tower and cooling water circulation
- Water pre-treatment and demineralization or softening operations
- Testing effluent and flare systems
- Steam blowing lines and commissioning the low-pressure steam systems
- Commissioning the medium pressure steam systems
- Bringing in fuel gas including leak checking
- Firing auxiliary or main boilers
- Starting main process in steps
- Sending product to storage
- Slowly raising plant rates
- Starting the performance test

OBJECTIVE 4

Explain the roles and responsibilities in the design and construction of a new plant.

Owner

There are many different stakeholders in the design and construction of a new plant. They have different or related responsibilities during the phase design and construction phase.

The corporation that is paying for and will own and operate the new plant is called the owner. The owner is involved with the work before the detailed design engineering starts, including:

- Obtaining the necessary government permits to construct and operate the new facility
- The feasibility study
- Determining the plant location
- Obtaining funds for the new facility

Staffing the new facility is also the responsibility of the owner. The new plant requires operations personnel, maintenance people, and all types of support staff such as laboratory technicians, human resources, and safety personnel.

Training the new staff is also the responsibility of the plant owner. Often the new staff comes from existing facilities with the same owners, but staff are also hired from outside the company. All staff must become familiar with the new facility and management system.

The owner and the engineers employed by the owner must be involved in all stages of the design and construction of the new plant. The owner's engineering department is heavily involved in the conceptual and engineering feasibility studies for the new plant. Most of the detailed engineering is contracted to the design engineering company. The design engineering company may or may not be the same company that is doing the construction of the plant.

Designers

The detailed engineering or design engineering is usually contracted to an engineering company with experience designing the type of plant under construction. The design engineers are responsible for the following tasks:

- All detailed engineering in the design of the process
- Preparing drawings and specifications for all engineering disciplines in the plant
- Preparing vendor catalogues for ordering material for the plant
- Preparing documents for construction companies to bid on the construction of the plant
- Evaluating bids for the supply of material and the construction of the plant
- Issuing construction contracts after the bids have been evaluated. The design engineers may also be contracted to follow up on the construction contracts, make sure the time lines are met, and that the specifications are adhered to
- Using computer aided drafting to produce three-dimensional images of the plant



General Construction Contractor

The general construction contractor has the overall responsibility for building the plant. The general contractor does varying percentages of the work and subcontracts out other sections of the work. The general contractor handles the following types of jobs:

- Purchasing the required material as specified in the design specifications
- Supplying and supervising the trades people, such as pipe fitters and welders, electricians, instrumentation technicians, quality control experts, labourers and scaffolding crews
- Scheduling and planning of the overall project based on the plant construction timetable

Subcontractors

The general contractor hires subcontractors to do specialized work. The subcontractor can do this work more economically than the general contractor. The types of jobs often contracted out are:

- Cooling tower construction
- Construction of buildings such as warehouses, motor control centers, and control rooms
- Installation of specialized systems such as control systems, vibration monitoring systems, and fire alarm systems

Construction of large portions of a plant, such as the steam generator for a coal fired power plant, can also be contracted out.

Quality Control (QC)

Various QC personnel handle the quality control during the construction of a new plant. Basic QC, such as x-raying of piping and steelwork, is usually conducted by subcontractors under the control of the general contractor. The general contractor can also conduct all of the pressure testing of the piping to check that the plant has been constructed according to the design drawings.

The engineering company's QC people or the owner may also be involved. There are specialized inspection tasks they are suited to such as:

- Shop inspections of pressure vessels
- Witnessing the shop balancing of high speed rotors for turbines and compressors
- Verifying the piping systems have been built to the design specifications

Operations Staff

The main task for operations people is to learn as much as possible about the new plant before they start it up. They need to know the processes in detail. The plant designers may put on training courses to explain the operation of all processes and the functions of the main control loops. Some of the duties of operations people during the construction phase of the project include:

- Learning the piping details of the new plant and the punch listing. Punch listing lists the construction deficiencies of a piping system.
- Line blowing or trash blowing. This process cleans the debris out of a piping system. The debris items include welding slag, rags, rust, debris, and liquids used to pressure test the piping.
- Leak testing of piping systems, such as vacuum systems. Often the flanges are wrapped and a small gas (air or nitrogen) pressure is put on the system to detect leaks.
- Checking for proper rotation and test running motors and pumps
- Steam blowing of the piping that supplies turbines. Process piping is often cleaned of debris by blowing with air.

During the plant start or commissioning, the operators take control of the plant systems and start up the plant. All equipment must be watched very closely during this phase.

Often extra operators are used during startup, for training and to help with the commissioning of new equipment.

Maintenance

The plant maintenance staff must also learn as much as possible about the new plant and its equipment. Some of the duties of the maintenance staff include:

- Learning the new plant processes and safety procedures
- Becoming familiar with the new equipment and how to maintain and repair it
- Ordering spare parts
- Witnessing the shop run-in and balancing of rotors for high speed equipment



OBJECTIVE 5

Explain how the design and construction of a new plant are administered and controlled.

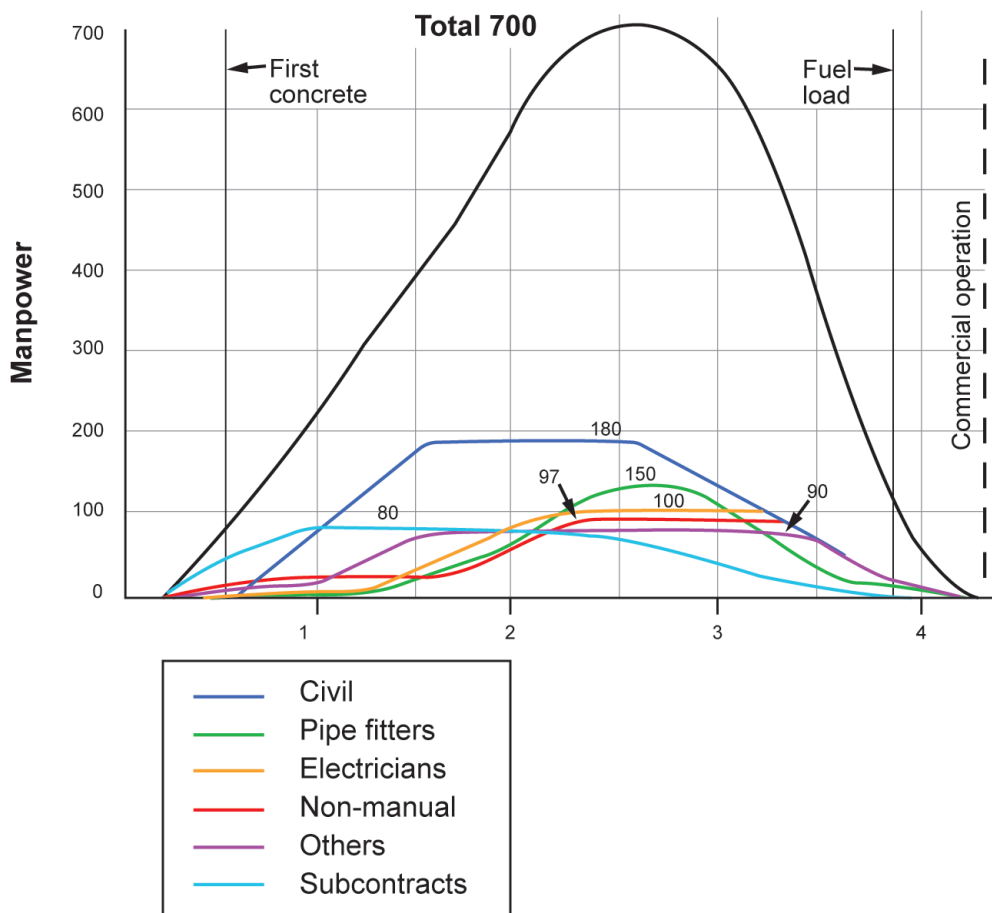
ORGANIZATION OF THE PROJECT

The company building the plant must decide how much work on the project its own employees can do in-house. It then decides how and with what firms to contract the remaining work.

Each project is organized according to the scale of the plant and the requirements of the owner. Although no projects are organized exactly the same way, there are a number of general options. Combinations of each type can be tailored to meet a particular project's requirements.

Figure 2 illustrates the number of workers on a power plant construction site. The job must be well planned and coordinated so the workers complete their jobs by the startup date. A chart such as Figure 2 will enable the planners to predict how many workers are required in each trade at any given time, so that the required staffing levels for each week can be planned for and organized in advance.

Figure 2 – Workers on a Construction Site



Design – Bid – Build

In this arrangement the owner gets a scope definition with basic engineering partly complete. An engineering company completes the detailed engineering. When working drawings and designs are completed, bids are sent out for the construction of the plant. Construction is contracted out to a general contractor. The plant scope is not finalized until late in the project. The cost of the project cannot be finalized until all changes in scope have been completed. Different approaches used for design and construction, which are detailed in the following sections, include Reimbursable Engineering Procurement, Design – Build, and Lump Sum Engineering Procurement.

Reimbursable Engineering Procurement Construction (EPC)

Procurement is the purchasing phase of the project. In the Reimbursable EPC arrangement, with the basic engineering about 10% complete, an engineering company is selected to do the detailed design, procurement, and construction. The engineering company is paid the actual cost plus a fee for each project phase. The total cost of the project is not known until all phases of the project are complete.

Design – Build

With the basic design engineering about 20% complete, the owner selects a company to complete the detailed design, order the equipment, and construct the plant. The entire project is done based on a final, lump sum payment. Risk for the owner is reduced, as the price for the entire project is fixed up front. The final payment is often made after the performance run of the plant has been completed. This type of arrangement combines the roles of the designer and the general contractor.

Lump Sum EPC

When the basic engineering is about 20% or more complete, the owner selects a company to do the design engineering. The scope has to be well defined upfront, so the companies bidding on the work can accurately estimate the costs of each phase. With the design engineering complete each phase is put out for bids on a lump sum basis. A contractor is selected for each phase of the project.

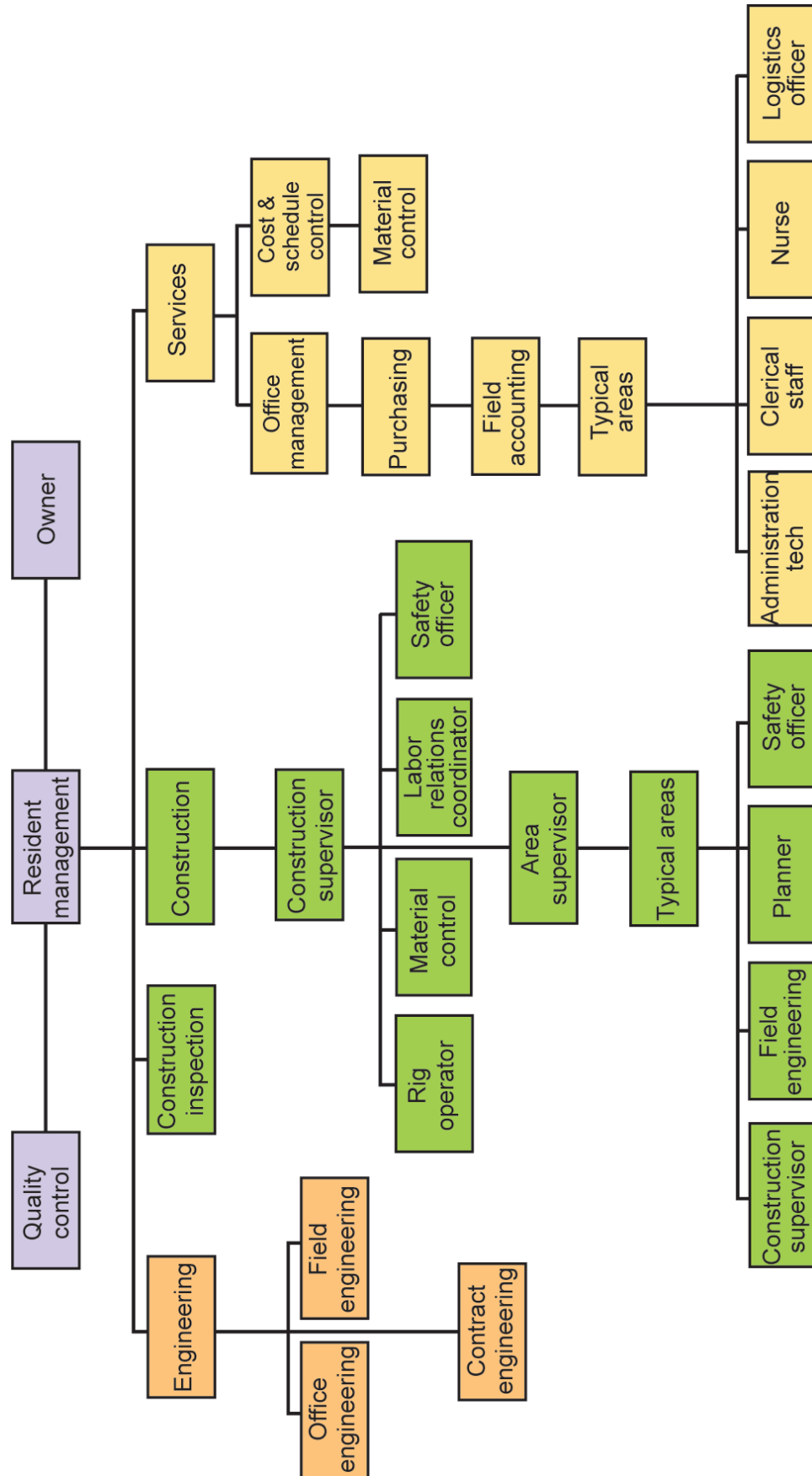
Construction Field Administration

When the general contractor has obtained a contract by any of the methods described a plan for scheduling and completing the construction is developed. Extensive planning and scheduling is required for a large engineering project. There must also be a method of monitoring the construction progress against the construction schedule. Figure 3 shows a typical organizational chart for a construction project. This chart is for staff at the construction site. The top level of structure shows the owner, or company, that is building and will own the new facility. The resident manager is the plant manager. The headquarters engineering site support is the engineering company's head office staff that will support the local engineering office.

The next level of diagram breaks out the larger groups at the site into engineering, construction staff, and services or office functions. The construction group contains all the construction related staff, from supervision to safety personnel.

The services area contains groups such as purchasing, accounting, and document control.

For the project to be completed in a timely and cost effective manner, all personnel must function well and communicate effectively with each other and with all groups.


Figure 3 – Construction Field Organization Diagram for a Power Plant


CHAPTER QUESTIONS

1. What does ASME stand for? List the ASME Codes used for the design and construction of pressure equipment in Canada.
2. Briefly describe the steps involved in developing specifications and contracts for new plant installations.
3. Explain the difference between an engineering study and detailed plant engineering.
4. How can change orders affect the price of a project? When is the least expensive time to make changes in the design drawings?
5. List five duties of operations personnel during the construction phase of a new plant construction project.
6. Explain the difference between the Design - Bid - Build method for plant construction and Design-Build method.



Management and Supervision

LEARNING OUTCOME

When you complete this chapter you should be able to:

Describe the roles and basic competencies of a supervisor and manager.

LEARNING OBJECTIVES

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

1. *Define management and explain the general functions of management.*
2. *Explain how management goals and objectives are developed through planning.*
3. *Describe how business decisions are made.*
4. *Describe methods of selecting new employees.*
5. *Explain how employees are trained.*
6. *Explain how to provide leadership and motivate employees.*
7. *Explain how to manage employee performance and behaviours.*
8. *Describe proper communication skills by writing a formal report.*



OBJECTIVE 1

Define management and explain the general functions of management.

INTRODUCTION

As power engineers gain experience and expertise, they may become increasingly involved in management and supervision. Their technical role decreases, and their prime responsibility changes to guiding and directing other employees with a focus of meeting business objectives. This requires new skills and a shift in job activities. Not all power engineers will want to give up direct technical involvement but they will realize that a role in management can be very satisfying.

This module is a summary of what is required to be an effective manager, and further training expands and builds on the ideas presented here. As well, management is a constantly changing area and improvements are made as new insights are gained.

ORGANIZATIONS

In order to understand management, it is necessary first to discuss organizations. An organization is a group of people that is systematically arranged to accomplish a specific purpose. There are many different types of organizations such as government agencies, oil companies, manufacturers, not-for-profit organizations, service companies, sports teams, and many more.

Despite their diversity, organizations have three common characteristics as shown in Figure 1:

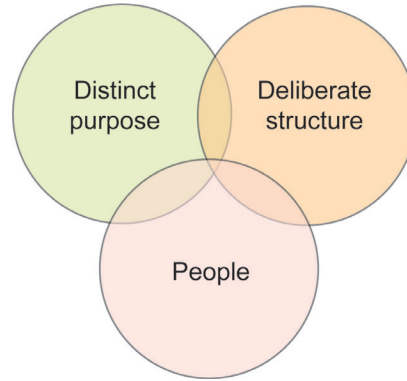
1. A distinct purpose
2. People
3. A deliberate structure

Every organization has a distinct purpose that is expressed by a goal or set of goals. These goals may change over time but often remain fundamentally the same.

Each organization has people that have a variety of roles and activities focussed on realizing the purpose of the organization.

There is a structure to the organization that governs activities and defines and limits the behaviour of its members. This is evident in not only the organizational structure that controls activities in specific ways, but also in the practices and procedures that are adopted, either formally or informally.

Figure 1 – Characteristics of Organizations



Organizations have changed substantially in recent years due to societal, economic and technological influences. Computers and information technology, employee expectations and global competition are examples of these influences. The constant in this change is the need for managers and the crucial role they play in management of changing organizations.

Power engineers often work in organizations that are involved in power generation and production, refining, and transportation of hydrocarbons and petroleum products. The focus is largely on effective and efficient operation and maintenance of a large variety of machinery and other physical assets. This results in a specific type of organization that is best suited to meet these requirements and some specific management requirements.

MANAGERS

Management is the prime responsibility of managers and supervisors. A manager is a member of an organization who has responsibility for integrating and coordinating the work of others. This may entail direct responsibility for a well-defined group of people in an organization or indirect responsibility for the coordination of a work team composed of individuals from across an organization or even from other related organizations. Many employees are directly involved in planning, making decisions and monitoring performance.

There are three categories of managers: **first-line managers**, **middle managers**, and **top managers**.

First-line managers are often called supervisors or team leaders, and they directly coordinate the work of non-managerial employees. Many power engineers assume the role of a first-line manager.

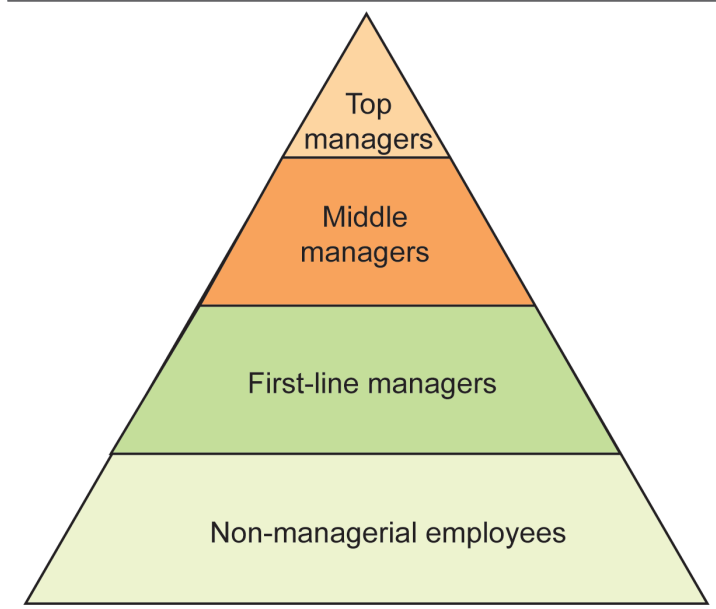
Middle manager roles usually involve coordinating and integrating the activities of various work teams or organizational units. There may be several levels of middle managers between the first-line managers and top managers especially in large organizations.

Top managers are responsible for making organizational decisions and setting policies, strategies, and objectives for the entire organization. Although many smaller decisions are made by first-line and middle managers, the final decision making responsibility lies with the top managers.

This produces a hierarchical structure such as the one shown in Figure 2. Although this type of structure appears to be more of a traditional one with a rigid hierarchy, it can also represent a more flexible approach.



Figure 2 – Organizational Levels



WHAT IS MANAGEMENT

Management is the process of coordinating and integrating work activities so that they are accomplished efficiently and effectively. Efficiency is the ability to make use of resources to transform inputs into outputs with minimum expenditure of resources and maximum benefit. It is also important to be effective, that is, to ensure that activities are completed as required.

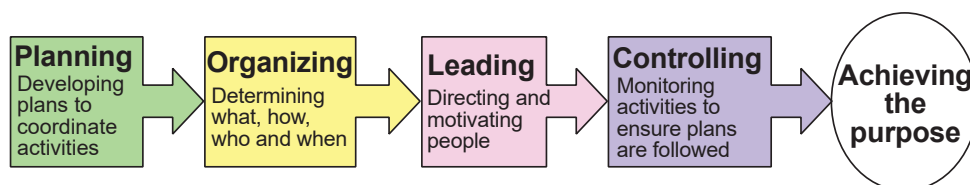
Efficiency and effectiveness are not necessarily dependent on each other. It is quite possible to be very efficient but to produce very little output

It is possible to be very effective but to do so inefficiently.

FUNCTIONS OF MANAGEMENT

All management functions can be condensed into four areas: planning, organizing, leading, and controlling. They are linked, as shown in Figure 3, to support the achievement of organizational goals.

Figure 3 – Functions of Management



Planning is an activity that involves establishing organizational goals, establishing a strategy for achieving the goals, and developing plans to integrate and coordinate activities at all levels.

Organizing is deciding how people are grouped, determining what activities are to be accomplished, how and when they are to be done, and who is to do them.

Leading involves managers directing, coordinating, and motivating employees in their work. Whenever necessary, the manager resolves conflicts among employees.

Controlling is monitoring the performance of activities by comparing them to previously set goals and objectives. If there are significant deviations, management evaluates what has to be done to close the gap and correct the deficiencies.

The day-to-day responsibilities of a manager require him or her to be flexible, creative and able to integrate management functions to address needs that arise.

MANAGEMENT ROLES

Sometimes it is more accurate to describe the functions of a manager by looking at their job roles. A study done by Henry Mintzberg concluded that managers perform ten different but interrelated roles that can be grouped into three areas: **interpersonal**, **informational** and **decisional**.

Interpersonal roles involve:

- Interrelating with others as a symbolic figurehead (such as presenting an award)
- Being a leader to motivate employees
- Liaison or interacting with others

Informational roles include acting as:

- A monitor (seeking and receiving information)
- A disseminator (transmitting information)
- A spokesperson (official transmission of information to outsiders)

Decisional roles break down into one or more of the following:

- Entrepreneur (organizing strategy and review sessions to develop new programs)
- Disturbance handler (corrective action for unexpected problems)
- Resource allocator (identifying and scheduling activities)
- Negotiator (discussing and resolving issues)



OBJECTIVE 2

Explain how management goals and objectives are developed through planning.

BASICS OF PLANNING

The first function of management is planning. Planning has three aspects:

1. Defining corporate goals and objectives
2. Establishing strategies for achieving goals and objectives
3. Developing specific plans for implementing goals and objectives

It may seem that planning is carried out only by top level managers, but planning occurs at all levels as a consolidated effort by all employees.

In this module, only formal planning is discussed. Formal planning requires that plans are developed, documented and clearly communicated.

Planning provides direction both to managers and to non-managerial employees. If everyone knows what the overall objectives are and what part they play, they can coordinate activities and work together to achieve them without overlap and duplication.

Planning forces managers to look ahead, identify needed changes and develop appropriate responses. This reduces uncertainty and manages change more effectively.

Planning develops objectives that can be used in the management function called “controlling”. With clear objectives, it is possible to compare them against actual performance and take corrective action if needed.

TYPES OF PLANS

Plans are categorized in several ways. The most common way of describing plans is to divide them into the following types:

1. Breadth: strategic vs. operational
2. Time frame: short-term vs. long-term
3. Specificity: specific vs. directional
4. Frequency of use: single use vs. standing

Strategic vs. Operational

Plans are divided into strategic plans and operational plans. Strategic plans describe overall corporate objectives over a long time period. Operational plans cover more detailed aspects of how the objectives are to be achieved, usually for a short time period.

A major difference between the two types of plans is that strategic plans include objectives and operational plans are concerned with how these objectives are implemented. In larger organizations, strategic plans are the domain of top and middle managers, and operational plans are the primary responsibility of first-level managers with some assistance from middle-level managers.

Power engineers with managerial responsibilities are involved directly in operational plans. They also participate in the development of at least middle-level strategic plans and incorporate the resultant objectives in their operational plans.

Short-term vs. long-term

Most operational plans are short-term (usually a year or less, and often weekly or monthly). For this reason, they are usually short, specific and focussed.

Long-term plans are typically 2-5 years in length with yearly reviews and updates. Their content is general.

Specific vs. Directional

Specific plans have detailed objectives and outline the means to accomplish them. Specific plans are most applicable to short-term operational plans where the possible influence of external factors is easier to anticipate.

A directional plan lays out objectives but not necessarily how they are to be achieved. Directional plans are often more appropriate for strategic and long-term plans. The wider scope of objectives and longer time period introduce uncertainty that is likely to require adjustment and flexibility. A directional plan provides this without requiring time-consuming and potentially disruptive changes to the plan.

Single Use vs. Standing

Some plans are designed to address specific situations that only occur once, such as moving to a new office building. Others are designed to address repetitive procedures and are prepared on a regular basis. Examples of competitive procedures are the corporate plan, the yearly budget and the weekly work schedule. Other plans, such as ones for mechanical breakdowns, are available for times when they are needed.

A good example is a plan to perform a root cause analysis when a major failure occurs. It is triggered only when required, but it is nevertheless worthwhile to have a plan in place so that the root cause analysis can proceed without delay.

OBJECTIVES

With a good understanding of planning, it is now possible to discuss objectives. Objectives and goals are usually interchangeable terms.

What Are Objectives?

Objectives are the desired outcomes for the organization, groups within the organization, and individuals. Objectives are the basis for making decisions. Objectives are essential for controlling because they are the criteria which need to be measured and the criteria against which actual performance is compared.

An organization has a set of objectives. In addition to the financial objectives around revenue, cost, earnings, and profit, organizations may have objectives dealing with employee and public safety, product quality, production, reputation, superior service, environmental stewardship, and social programs.

Objectives often have a hierarchy with general objectives at the top and more specific objectives at lower levels. Although top corporate objectives are important guideposts to the purpose and goals of an organization, it is the middle and lower objectives that are most relevant to lower-level managers because they are the ones who determine action plans that impact employees.



Developing Objectives

There are various ways to develop or set objectives. The traditional way is for top-level managers to develop the overall corporate goals and targets, and then sit down with the middle managers to review these goals and targets and identify who will be accountable for meeting each target. The middle managers evaluate their departmental targets and goals. With their front line managers and team leaders, they develop strategies to meet these targets and goals. The team leaders and supervisors then work together with all of the departmental employees to implement the strategies and realize the goals. The objectives form a network of objectives that are interdependent and linked.

A weakness of the traditional approach is that it fails to consider input from all parts of an organization. This may create unrealistic objectives and difficulties in obtaining success.

Many organizations now use **Management by Objectives (MBO)**. Employees involved jointly develop objectives and progress is periodically reviewed. Rewards are tied directly to performance as it relates to agreed objectives. Many organizations find MBO to be effective and to provide important motivation to both managers and employees.

MBO has four basic elements:

1. Specific goals and objectives
2. Joint decision making by participants
3. An explicit time period
4. Performance feedback

The steps in a typical MBO program are:

1. Overall objectives and strategies are formulated by top level managers.
2. Objectives are allocated to various divisions or business units.
3. Managers of divisions or business units set specific objectives in collaboration with their superiors.
4. The next level of managers, usually at the department level, collaborates with their superiors to develop objectives specific to their area.
5. Action (or operational) plans that describe how the objectives are to be achieved are agreed upon.
6. Action plans are implemented.
7. The plans are reviewed on a regular basis and feedback is provided.
8. Performance-based rewards are given when objectives are successfully completed.

Objectives for Power Engineers

Power engineers are likely to be involved in objectives related to the operation and maintenance of machinery and equipment. The primary corporate goals may focus on production of oil, gas, electric power or petrochemical products, the manufacturing of goods, or the provision of a service. Additional goals are safety, the environment and financial aspects.

These high level goals may result in more specific objectives for the power engineer such as:

1. Plant performance and capacity
2. Availability and reliability of equipment
3. Compliance with regulations
4. Safety of employees based on incidents and accidents
5. Environmental compliance (e.g. emissions requirements, spills)
6. Minimization of downtime
7. Maintenance costs



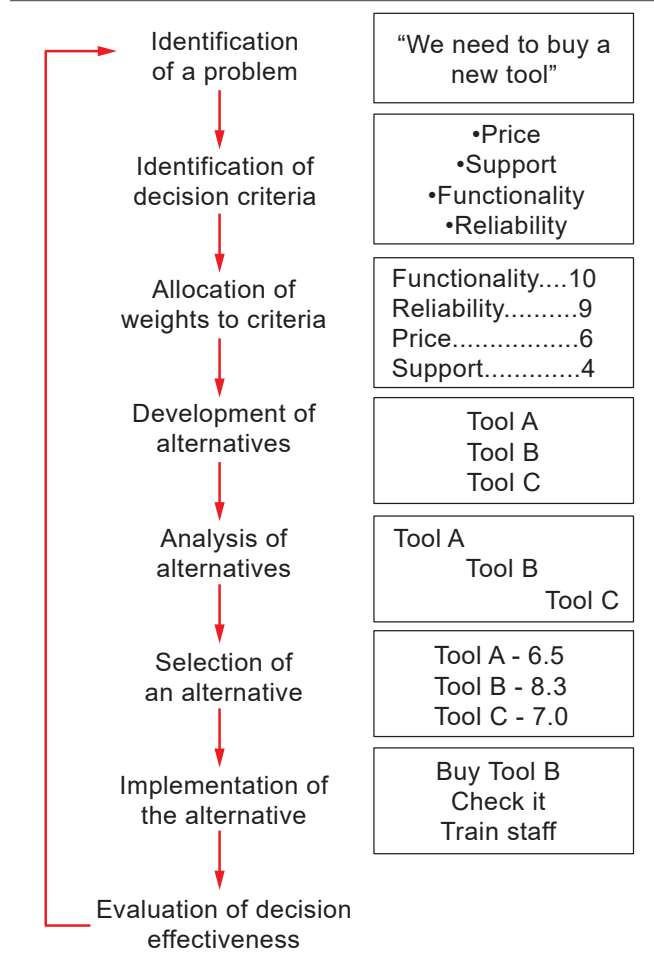
OBJECTIVE 3

Describe how business decisions are made.

DECISION MAKING PROCESS

The ability to make effective decisions is the most important attribute of a successful manager. The simple view of decision making is that it is choosing between available alternatives. In practice, it is a comprehensive process with risks and uncertainties. The eight steps in the decision making process are illustrated in Figure 4 with an example and a further explanation below.

Figure 4 – Steps in the Decision Making Process



Identifying a Problem

The first step is to recognize that there is a problem. For example, in the situation shown in Figure 4, an employee decides that a new tool is necessary because the old one does not work well. The manager may be unconvinced because the work is still able to proceed as expected.

Identifying the problem is therefore often the most difficult step. It is always possible that different people will perceive the problem differently. For a problem to be identified for action, managers must take the following steps:

- Accept that there is a discrepancy to be resolved and understand the need to take action.
- Assign or approve resources to rectify the problem.

Without these actions, a problem may be delayed, ignored or denied.

Identifying Decision Criteria

The next step is to identify the criteria that need to be considered when making the decision. At this point, the criteria are only listed and no order of importance is determined. The criteria relevant to making the decision are established. The best way to test this is to ask whether the criterion will sway the decision to a specific solution if all other factors are equal. For example, if the colour of the tool is irrelevant to its use, it should not be included as a decision criterion.

Allocating Weights to Criteria

Once the criteria are established, a system to allocate weights that establishes their importance or priority in making a decision. Because a decision is made between available alternatives, relative weights are assigned. Usually a scale is used such as 0-10. The most important criterion is given a weighting factor of 10 and the remaining criteria are assigned accordingly.

Developing Alternatives

Now the possible and available alternatives are identified and listed without any analysis. The only factor is that the alternative can solve the problem although it may turn out later that there are significant deficiencies. It is best not to rule out possible solutions unless they are obviously unsuitable.

Analyzing Alternative

Each alternative is analyzed carefully against all of the criteria. A score of 0-10 (or some other suitable scale) is given for each criterion. As much as is possible, objective assessments based on verifiable facts should be used. For some criteria, the assessment may be mostly subjective since hard numbers are often hard to come by. Cost is easy to rate but sometimes there are factors that may make even this criterion less than objective. The assigned scores are multiplied by the weighting factor and the values for the criteria are added together to give a total score.

Selecting an Alternative

In theory, the best alternative is the one with the highest score. If there are several scores that are very close to each other, the factors and even the weighting factors may have to be reconsidered. Political or other factors may present themselves and influence the final result. The original need to resolve the problem may be revisited once the alternatives and solution are known. The cost may be too high for the budget and the purchase is delayed until the next year.

Implementing the Alternative

This step is concerned with implementing the chosen alternative and success is not achieved until this occurs. Acceptance of the decision is advanced if affected staff is involved in the decision making process from the beginning.



Evaluating Decision Effectiveness

Every manager ensures the decision has been effective in solving the problem. Sometimes it becomes evident the problem still exists and has resurfaced elsewhere. A new evaluation or review is called for, giving careful evaluation as to which step is responsible for the failure.

MAKING DECISIONS

Decisions do not need to be time-consuming or difficult to make. The larger the decision in terms of impact and resources needed, the more effort required for the decision making process.

If an incorrect decision is made, it is tempting to blame the process. A rational approach along with a sound process does not always give the right answer. This is based on the assumption that the correct decision will be made if:

- the problem is clearly identified
- there is no conflict in goals and objectives
- all of the options are known and understood
- there are clear preferences with respect to the evaluation criteria that do not change with time
- there are no time or cost constraints
- the desired alternative is always the one with the maximum payoff

Unfortunately, a pure rational approach is not always feasible and decisions are often made without complete analysis. An intuitive decision may actually be the most efficient way to make a decision if a manager has experience and a thorough understanding of the options. The first time a certain tool is purchased, a detailed evaluation is necessary. Its replacement after a few years may be accomplished with only a cursory analysis of criteria that have changed.

In these cases, managers may have to be prepared to defend their decision making process to others who may conclude they are not applying due diligence. The approach used to make a decision is somewhat dependent on the type of problem. Straightforward and common problems fit well into a rational approach and decisions become fairly easy to make. Some problems may require innovation or creativity to resolve, particularly when it comes to identifying alternatives and analyzing them.

In summary, the ability to make decisions and their ultimate success are key challenges for a manager.

FURTHER CONSIDERATIONS

Decision making is often confused with troubleshooting, because so many decisions are made in reaction to a crisis, problem, or breakdown that has occurred. Whenever possible, it is far more effective to be **proactive** about problems rather than **reactive**. This requires looking forward to the potential problems that have not yet occurred, and taking steps to avoid them. It is almost always more effective in terms of cost and time to deal with issues proactively, and thus avoid the need to be dealing with a breakdown after the fact.

Effective decision making is also dependent on having the appropriate people involved. Those that have relevant knowledge and experience, and those that will be responsible for managing the outcome of a decision, need to be included in the process. It is almost equally important not to involve people who do not have any stake in the decision, or who are not able to contribute effectively, since they will undermine the process and its results. Good decision making means that informed decisions are made, based on all available information, assumptions, and predictions. As a rule, day to day decisions are more efficiently and effectively made when they are made by the people that are most directly affected by them. This has led to many organizations reserving the long-term **strategic** decisions for managers, but **empowering** employees to handle the routine **tactical** decisions every day.

Similarly, the **implementation** of a decision will only be effective when it is made perfectly clear who is accountable for it, and the accountability should be at the level of the people most directly affected by it. There is likely to be a need to document the factors that have led to a decision in order to **justify** it to higher levels of management by means of a formal **business case**, and there also needs to be some follow-up by management to ensure that the implementation has been completed and that the desired results have occurred. However, the accountability for action is most effective when it is held by the people on the organization's front lines.



OBJECTIVE 4

Describe methods of selecting new employees.

HUMAN RESOURCE MANAGEMENT

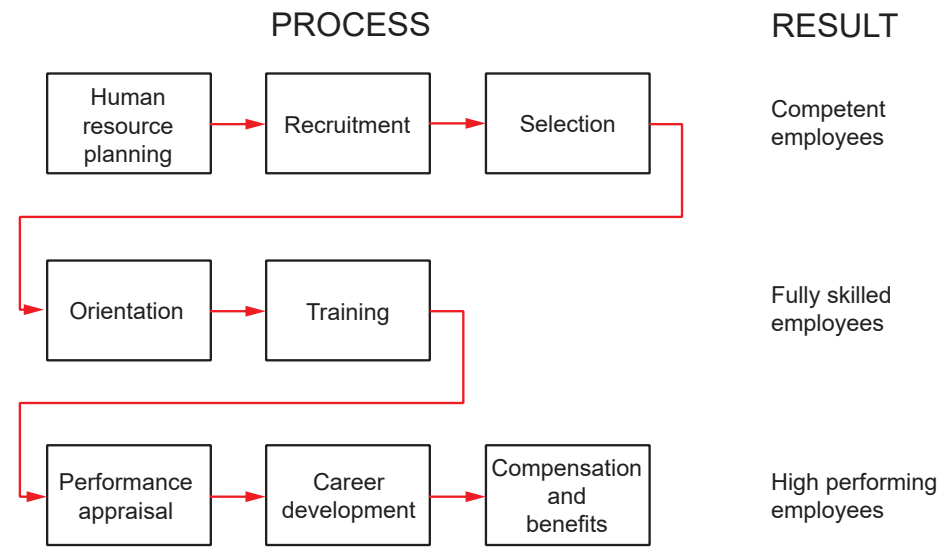
Human Resource Management is attracting and retaining qualified staff. In large companies, an entire department is focussed on this task. In addition, all levels of management are heavily involved in activities related to human resource management.

There are three major functions of human resource management.

1. Identification and selection of employees
2. Ensuring employee competency
3. Retaining and rewarding employee performance

These functions break down further into eight steps to form the human resource management process (see Figure 5).

Figure 5 – Steps in the Human Resource Management Process



Identification and Selection of Employees

The first role of human resource personnel is to work with department managers to evaluate their existing staffing levels and structures, and to determine if they are effectively and efficiently managing the current and predicted work loads. Once the structure and the staffing levels have been decided upon, then job descriptions for each position are developed, validated, or upgraded to match current roles and responsibilities. When the job descriptions have been completed the human resources personnel can begin the task of identifying the number of employment candidates that are needed and the particular skill sets that will be required of each candidate.

Human resource planning translates corporate objectives into staff requirements and ensures there is the right number of people with the right skills at the right place and time. This is done by assessing current human resources (by performing a human resource inventory), predicting future needs and developing a program to meet those needs.

The remaining two steps in this function – recruitment and selection – are dealt with later in this objective.

Ensuring Employee Competency

A fully competent employee is the result of proper orientation and training as covered in Objective 5.

Retaining and Rewarding Employee Performance

Performance appraisal allows feedback and permits regular review of actual performance as compared to objectives. Opportunities to participate in different work assignments are part of career development. Compensation and benefits are the primary means of rewarding employees although other ways are also used.

RECRUITMENT

Recruitment is the process of locating, identifying and attracting capable applicants. The first place organizations look is internally. This is often followed by advertisements and the use of recruitment agencies.

The roles and responsibilities of a position will influence where and how the recruitment takes place. The greater the level of responsibility managed by a position, the wider the search will need to be to source a greater possible knowledge base and skill level. The higher the knowledge base and skill level that are required, the more time it generally takes to locate a suitable candidate and fill the position.

SELECTION

The selection process is the method used to evaluate potential employees so that the most appropriate candidate is hired. Success in the selection process is measured not only by hiring the right person but also by rejecting unsuitable candidates. Hiring the wrong person is costly because it includes the cost of training, cost due to incompetence, cost of removing the candidate and the cost of further recruiting and selection.

A manager may use one or more methods to achieve success in the selection process.

The application form is a universal method used to do initial screening, particularly for those candidates that apply externally and are unknown to the manager. Its purpose is to communicate education, skills, accomplishments and experience but it is rarely sufficient by itself. The candidate usually provides a resume with the application form.

Written tests are sometimes used during the candidate selection process. These tests usually involve general knowledge exercises together with site-specific or process specific work assignments to give the prospective employer as much knowledge of the candidate's current knowledge and skill level as possible. They can be effective but do require more preparation or the use of an outside agency. The information is then combined with data from a formal interview to assist in matching the best candidate to a specific position.

The most common method of candidate selection is the job interview. It is an essential part of the selection process. The candidate meets with the supervisor, others from the same department, possibly representatives from other departments and sometimes a human resources person.



Although the interview will probably never be replaced, it has significant drawbacks and research has shown that it is often not especially effective. The reasons have to do with both the interviewer and the interviewee.

The interviewer, or often an interview team, is well prepared and not only has a good knowledge of required technical or job skills but is also able to show superior communication and interpersonal skills. If the interviewer is very formal and “too cold,” interviewees may not react well to the interview. It is easy to come to a quick conclusion about a person’s suitability and to be swayed by biases. On the other hand, it is important to try and uncover behaviours and skill deficiencies that may cause dissatisfaction with the chosen candidate.

Some people do not interview very well and tend to come across negatively because an interview can be quite a stressful experience. Once they fit into the work group, they may in fact be an excellent choice. Others are very impressive in the interview but later have problems in the work environment.

The following suggestions are made to maximize the effectiveness of an interview:

1. Prepare a fixed set of questions for all candidates.
2. Agree on detailed job requirements prior to interviews and make this available to the applicant.
3. Acquire knowledge of the background and experience of the applicant before the interview.
4. Ask some behavioural questions that show how the person may behave in applicable workplace situations.
5. Use a standardized evaluation form.
6. Take good notes during the interview. Review the notes as a group after the interview.
7. Allow sufficient time and avoid short interviews that will lead to quick decisions.

The candidate needs time to ask questions about the job.

Once a candidate is selected, a background investigation and a reference check are done. The background investigation verifies application data, such as educational qualifications and previous work experience, performance, and attitudes.

Reference checks, usually by phone, provide a third party opinion of the applicant and, if documented properly, also act as a protection for the interviewer. Questions verify experience and deal with job requirements. Reference letters are rarely of value since they are mostly vague testimonials that add little useful information to the selection process. Reference checks need to follow a formalized process that includes a standard set of questions to ensure that the most comprehensive information is always collected for each candidate.

OBJECTIVE 5

Explain how employees are trained.

ORIENTATION

The purpose of orientation is to smooth the transition of a new hire into an organization. Larger organizations have corporate policies and procedures that cover everything from human resources information such as work hours, overtime, pay procedures, benefits, and harassment policies to organizational objectives and plans, to specific work procedures such as safety, expenses, vehicles, tools, and materials requisitions.

A formal introduction to key staff and a general tour of the plant or facilities is common. Power engineers also require a more structured and detailed review of equipment, operational and maintenance practices and location of information such as equipment manuals and maintenance history. This important concept is covered in detail in the next section.

It is important that new employees are allowed sufficient times for familiarization before actual job tasks are assigned. It is easy to swamp new employees with backlogged work and to set them up for failure. Another employee is often assigned as a mentor for the first few months to assist with common procedures.

TRAINING

Many incidents, equipment failures, and a large amount of lost production can be attributed to human error. All occurrences of human error can be prevented and it is very important to identify the root cause of each incident so that the problem can be addressed and the potential for reoccurrence eliminated. Incorrect behaviours are caused by either a person's lack of understanding, training, and knowledge, or by a personal choice to make the wrong decision. It is very important that a formalized process is in place to objectively identify the cause of all incidents so that the best response is followed to mitigate the problem.

Training programs are directly connected to the job description and the level of responsibility held by the position. A good training program will evaluate the knowledge, experience, and competence of the candidate and compare this with the identified knowledge and skill sets required by the position. The program will then be tailored to meet the needs of each candidate. Training is a continuous, life long process and requires commitment from both the person being trained and his or her direct supervisor. The manager plays a crucial role in ensuring that a formalized training program is in place, along with a method for evaluating competency on a continuous basis.

Skill Categories

The skills that an employee needs are divided into three categories: technical, interpersonal and problem solving.

Most training, particularly for positions such as the ones that power engineers fill, relates to technical skills. Although the basis has been laid through a power engineering program, more training is required to adapt this knowledge to specific equipment and applications.

Interpersonal skills training is necessary because most employees are part of a working group or team and overall success is dependent on working effectively with other employees. Training in how to be a better listener, how to communicate more clearly, and how to reduce conflict is useful.



Problem solving or troubleshooting is an important skill for power engineers and many other positions. Some training is focussed on improving the ability to define problems, analyze situations, developing and assessing alternatives, and selecting solutions.

Training Methods

The two methods of training are on-the-job training and off-the-job training.

On-the-job training consists of work activities that are focussed on learning specific tasks. The employee learns by observing someone else doing a task and then repeats it while the other person observes. Another way is for the employee to execute various steps in a task in response to verbal instructions.

An example is learning how to do routine maintenance. For the first few days, the employee follows and observes the tasks that are being done. The experienced employee explains the steps and reasons behind the tasks while the employee takes notes. After a suitable time, the new employee starts to do the tasks while the veteran employee observes. The new employee repeats the tasks until able to perform them without assistance before being allowed to do them alone.

For new managers (or supervisors), on-the-job training is not as straightforward. It is often assumed that the new manager knows what has to be done. However, he may be unwilling to admit that he doesn't know. In professional and management positions, it is now accepted for a new employee to have a mentor or coach. The mentor passes on knowledge on how things are done and provides advice on how to resolve issues. A new manager is wise to find a mentor even if the organization does not have an official mentoring program.

Off-the-job training occurs outside the normal work environment and normally takes place in a classroom with others. Computer based and on-line training are popular because they reduce travel time and expenses.

Training for Employees

The manager or supervisor has responsibility for ensuring that employees are competent and skilled to complete assigned tasks. Training is a major way in which the manager enables success in the work group or team. There is a lot of satisfaction in helping others develop their skills.

There are structured and logical ways to plan for training employees. The following discussion focuses mostly on what a first-line manager or supervisor needs to do to ensure competency of non-managerial employees. These are the steps taken to set up a training program for employees:

1. Fully understand the job functions of the work unit. A typical team in which a power engineer is employed is responsible for the operation and routine maintenance of machinery. Examples of job functions are logging and monitoring of the equipment, start up and shutdown, and routine maintenance such as changing filters.
2. List the knowledge and skills required to accomplish these job functions. These skills include safety procedures, work procedures, operating procedures, maintenance procedures and documentation.
3. Determine the specific training required to support the skills needed for the job functions. This includes both on-the-job and off-the-job training.
4. Using the skills from step 2, perform a skills gap analysis which documents the current level of competency for each employee.
5. Identify the key areas for training that each employee will need, based on the roles, responsibilities, and tasks that his or her job requires.
6. Prepare an individual training plan for each employee taking into account greatest need, and constraints in time (not all training can or needs to happen at once) and budget (only so much money will be available).

One of the main barriers to training is the constraint of budgetary funds. Management is used to allotting a certain amount of money and allowing the manager to allocate this among the staff. However, if a supervisor finds that more training is appropriate because there has been a large turnover in staff and new staff are relatively inexperienced, it may be necessary and important to put a major focus on training. The above process allows the manager to establish this need definitively to their superiors and to justify additional expenditures. Management will be appreciative of this proactive and responsible approach to understanding and dealing with risk to the organization.



OBJECTIVE 6

Explain how to provide leadership and motivate employees.

LEADERSHIP

The third function of management is leading. Since the role of management is to direct and coordinate the activities of employees, managers spend a lot of their time interacting with employees to enable them to accomplish their work in the context of corporate objectives.

A lot of emphasis is placed on leadership and many different approaches and opinions exist on this topic. Leading includes:

1. Directing employees to accomplish tasks to meet business objectives
2. Motivating employees
3. Enabling communication between employees within the team and with others outside the work group
4. Resolving conflicts between members of the group

This objective provides a brief introduction to leadership and deals mostly with the aspects of motivation.

ORGANIZATIONAL BEHAVIOUR

The foundation of leading and leadership is a thorough understanding of behaviour. Behaviour in this context is known as organizational behaviour and includes both individual and group behaviour.

The purpose and value of understanding organizational behaviour is to explain and predict behaviour. Managers require this skill because their success depends on other people performing work. Managers want to explain and predict employee productivity, absenteeism and job satisfaction.

Individual Behaviour

Individual behaviour is based on an understanding of psychology and is concerned with attitudes, personality, perception, learning and motivation.

Attitudes reflect how someone feels about something. Attitudes relate to beliefs, opinions and knowledge and to the emotions that someone feels. The important thing about attitudes is that they lead to behaviours that may be either positive or potentially destructive.

Job satisfaction is the general attitude of an employee to their job and work environment. Job involvement is the degree to which an employee participates in their work and considers the work to be important for their self-worth. Organizational commitment is their loyalty to the organization and its objectives.

Employees try to maintain consistency between their attitudes and what they do. Sometimes they adjust their attitude if they end up doing something that was previously in conflict with their attitude. Many people will adjust a critical attitude towards another group if they are required to be a part of that group for any length of time. They become involved in some way that allows them to better understand what that group has to deal with. This is a valuable tool for a manager if attitudes are negative or disruptive.

Although there is much debate on this issue, it is generally accepted that a person's attitude is indicative of their future behaviour and can be used to predict how they may respond to work situations and conflicts. The understanding of attitudes permits the manager to anticipate and potentially avoid conflict.

Group Behaviour

Sociologists and social psychologists study the behaviour of groups of people. Group behaviour is not only the sum of the behaviours of its individual members. Groups exhibit unique behaviours that are not exhibited by individuals.

Formal groups can be divided into these types:

1. Command groups: traditional work groups that are a part of an organization with formal authority arrangements.
2. Cross-functional teams: a group of individuals with different skills brought together to accomplish a specific task, usually to resolve an operational problem.
3. Self-managed teams: independent groups that not only do their normal work activities but also share traditional management responsibilities such as planning, employee selection, and performance evaluation.
4. Task forces: temporary groups formed to accomplish a specific task.

Group behaviour reflects the interaction of its members. Groups go through five stages in their development:

1. Forming: people join a group because they are placed in the group or because they want to join.
2. Storming: group members try to establish their role in the group in order to obtain influence and power. There may be conflict as people jockey for position.
3. Norming: at this point, group members have established their position and role, and they have a common understanding of group expectations and correct behaviour.
4. Performing: the group is functional and is able to efficiently complete its objectives.
5. Adjourning: for temporary work groups such as committees and task forces or prior to reorganization, the last stage is wrapping up and completing the assignment. Members prepare for disbandment and recognize, reward and celebrate accomplishments.

MOTIVATION

Motivating employees is one of the most difficult things for a manager. A common misconception is that motivation is an attribute of an employee, as in "this employee is not motivated." In reality, motivation is the result of interaction between employees and their environment.

Motivation can be defined as the degree of effort that a person is willing to exert to reach organizational goals influenced by meeting a personal need. There are three aspects to motivation:

1. Effort or trying hard to be successful
2. Organizational goals as the focus of the effort
3. A need or an internal state that is unfulfilled and needs to be satisfied

Theories of Motivation

The need for achievement, power and affiliation are major motives in work.



Three-Needs Theory

One current approach to motivation is called the **Three-Needs Theory**. It proposes that there are three major motives in a work situation:

1. Need for achievement: the drive to excel, achieve and succeed
2. Need for power: the desire to have influence and have impact on the group
3. Need for affiliation: the desire to belong and have close personal relationships.

This model is fairly successful in predicting behaviours. Once managers understand what type of need is important to an individual, they can use that need both to achieve positive work results and also to increase the satisfaction of the individual.

Goal-Setting Theory

Goal-setting theory is based on the observation that working towards goals motivates employees. Employees with a high need to achieve benefit from the challenge of achieving difficult goals and moderately challenging goals motivate other employees.

Yet another approach focuses on the theory that employees respond to reinforcement. There is a wide range of reinforcers available that recognizes and rewards positive results.

Motivators

Successful managers and supervisors motivate employees by:

1. Enlarging the work scope to provide variety
2. Using realistic goals
3. Allowing people or small groups to complete and be responsible for larger tasks instead of portions of tasks
4. Providing flexibility for the employee in how and when a task is done
5. Recognizing extra effort
6. Having rewards that employees can strive for
7. Providing feedback, especially positive
8. Matching jobs and tasks to individual strengths and desires
9. Ensuring that there are no inequities between employees and with others outside the group

Most companies have a formal reward system that the manager may use. In addition, many successful managers have instituted their own means of recognition. Although monetary rewards are important, many employees value peer and company recognition even higher. Matching rewards to individual needs can be a very effective way to personalize and maximize the effectiveness of the reward.

OBJECTIVE 7

Explain how to manage employee performance and behaviours.

CONTROLLING

The fourth function of management is controlling. Even if objectives and plans are established (planning function), the work is organized (organizing function) and people are hired, trained and motivated (leading function), things may still go wrong. The final function of management, the controlling function, is aimed at measuring actual performance, comparing against the objectives and taking appropriate action.

There are many aspects to controlling, but the one discussed in this objective is how to manage the behaviour of staff.

BEHAVIOURAL CONTROLS

Because managers accomplish their goals and objectives through their employees, a prime responsibility is to verify that objectives are being met and behaviours, as they relate to the organization, are acceptable. The three ways that managers do this is by direct supervision, performance appraisal, and discipline.

Direct Supervision

Direct supervision consists of overseeing work on an ongoing basis and correcting problems as they occur. Some call this **Management by Walking Around** or **MBWA**. Using this method, many managers learn more about what is done in their workplace than from reading reports or from meetings.

The correct approach by the supervisor is to build positive relationships with staff. Many minor problems can be rectified before they become serious. It can be a good opportunity for positive feedback.

The manager should be aware that employees can easily exhibit a negative response to a supervisor “snooping around.” A constructive attitude on the part of the manager and a willingness to listen carefully go a long way toward preventing misconceptions about the purpose of direct supervision.

Performance Appraisal

Many companies use a formalized process of performance review to help them and their employees evaluate individual performance and progress, as compared to a previously agreed set of expectations. The performance review process includes the employee and direct supervisor getting together and developing a clear set of individual goals, objectives, and expectations for the employee. These are based on a number of elements including safety, training, skills development, technical competency, and behavioural components of the employee’s job. Then, usually once per year, the two parties meet to compare the employee’s progress against the expectations. It is important to highlight the areas where excellent and exceptional performance was realized as well as to identify areas where goals were not met, and identify correct responses to each. This must be a very objective process and should be augmented by daily or weekly input from the supervisor to the employee as to the quality of work and level of performance.

A structured form is commonly the basis of the review, sometimes with a rating scale. The ratings have general descriptions or traits and descriptions of demonstrated behaviours. They may be tied to objectives as a part of the “Management By Objectives” approach.



Discipline

When an employee's performance is not satisfactory or when standards, rules or regulations are not followed, a manager or supervisor may be forced to use discipline.

Discipline is the set of procedures that a manager follows if company standards are not followed. Most companies have specific guidelines and procedures, and a supervisor applies them carefully, often with assistance from the next level of management and the human resources department. Careful documentation is a critical component of discipline because facts can easily be forgotten or misinterpreted later.

Disciplinary problems can be divided into four categories:

1. Attendance: absenteeism, tardiness or abuse of sick leave
2. On-the-job-behaviours: insubordination, abuse of alcohol, drug abuse or failure to use safety devices
3. Dishonesty: theft, lying or falsifying information
4. Outside activities: working for a competing organization, criminal activities and other unauthorized activities

The way discipline is applied is sometimes called the “hot stove” rule because of the similarity with touching a hot stove. There are four aspects to discipline:

1. Immediacy: with a hot stove, the pain is felt immediately. The effectiveness of discipline decreases with the amount of time between the offence and the penalty.
2. Advance warning: from a young age, people know what happens when a hot stove is touched. Managers need to be clear about what standards have to be followed and what the consequences are.
3. Consistency: the results of touching a hot stove are consistent and the response to an infraction needs to be the same.
4. Impersonal nature: the stove does not differentiate between people. The manager must be impersonal as well and not favour some people over others. The penalty is directed at the rule violation and not the person.

Many companies have **Employee Assistance Programs**. Employees can be referred to the programs by management or contacted directly by the employee to gain assistance. This is a worthwhile way for companies to invest in people, their most important resource.

OBJECTIVE 8

Describe proper communication skills by writing a formal report.

PURPOSE OF REPORT WRITING

There are instances when a power engineer needs to write a formal report. This report may describe activities, analyze and evaluate a certain situation, or propose recommendations for improvements. It is important that the report is well written, and the information clearly communicated.

There are three basic elements to communication that must be kept in mind for effectiveness, whether the communication is verbal or written. They are:

- Know your audience
- Know your subject matter
- Know your desired outcome

For the report to effectively communicate:

1. The purpose of the report is clear and stated at the beginning of the report.
2. The contents of the report are structured as detailed below.
3. The report contains enough information to meet the needs of the reader but is as short and succinct as possible. If a greater level of detail is required, it is contained in appendices.
4. Good grammar and spelling are essential to clear communication. Bad grammar and spelling detract from the impact of the report and may cause confusion. Simple sentences are preferred over complex sentences.
5. Before issuing the report, ask someone else to read it over and offer suggestions for improvement.
6. Find examples of good reports and learn from them.
7. Use standard report formats if they are available.

ELEMENTS OF A REPORT

There are a variety of report formats. Even the elements mentioned below may differ depending on the purpose of the report, company or other standards, intended audience or the type of content.

Some people differentiate between a technical report and other business reports. Usually there is little difference between them except that a technical report will contain technical content.

A report can be broken down into three main elements:

1. Introductory components
2. Main content
3. Supporting information



Introductory Components

The introductory components consist of:

1. A title page: this contains the title, date of the report, author(s) and other identifying information such as the name of the company.
2. Abstract, introduction, or executive summary: for most reports, it is worthwhile placing a summary at the beginning, typically just after the title page. This provides a brief summary of the scope of the report and states relevant recommendations. It is intended for the busy executive who does not have time to read the whole report. It also provides a sharp focus for the report. Brevity is crucial.
3. Table of contents: list of chapters, sections, etc. It is usual to go down two to three levels, but not all levels of headings have to be in the table of contents if they are too detailed. It lists any appendices.
4. List of figures and tables: this is optional but is beneficial for longer reports.
5. Acknowledgements: another optional element which shows appreciation to contributors.

Main Content

The main content of the report is organized into chapters and sections with a consistent system of headings. For a short report, it is sufficient to have two to three levels of headings and longer ones may use four to five levels.

The amount of text under each heading may range from a paragraph to a page but should not exceed one to two pages.

The use of common fonts is preferred. Headings are often a sans-serif font such as Arial and the text is often a serifed font such as Times New Roman.

Figures are placed right after the text in which they are first mentioned. Each figure has a figure number and a title that describes it. Examples can be found in this module. Sometimes figures are all listed at the end of the report. A heading may be placed at the top of each page showing the name of the major section or chapter and a relevant logo.

The footer contains the page number. Some people prefer a small Roman numeral in italics (e.g. i, ii, iii, iv, etc.) for the introductory pages and then the usual Arabic version of the number (e.g. 1, 2, 3, etc.), but for small reports, this is not required. The footer may also contain the name of the report and the version number (if applicable) along with the date.

If the main purpose of the report is to propose recommendations, it is important to state them in the main body of the report and to summarize them at the end of the report.

Short quotations may be placed right in the text enclosed in double quotation marks and followed by a means of reference. Longer quotes are started on a new line, possibly indented, and are separated from the rest of the text. They do not need quotation marks but of course still need a reference.

Supporting Information

The following supporting information is included:

1. References: these are normally placed at the end of the report. There are a variety of styles found in textbooks and online sources that can be followed for specific formats.
2. Bibliography: this is a list of resources used.
3. Appendices: detailed information, tables and data are recorded in appendices so that the main report is easy to understand.
4. Index: this is a list of main topics and is not normally required.
5. Glossary of terms: sometimes it is worthwhile to list terms and define them for clarity.

CHAPTER QUESTIONS

1. State and describe the four functions of management.
2. Explain the traditional way of setting objectives and compare this to management by objectives.
3. List the eight steps to making a decision.
4. List four items that maximize the effectiveness of a job interview.
5. List four steps taken to set up a training program for employees.
6. What are four ways a manager can motivate an employee?
7. Describe the four elements of the “hot stove” rule to applying discipline.
8. Describe four important aspects of writing a formal report.



Plant Maintenance

LEARNING OUTCOME

When you complete this chapter you should be able to:
Describe plant maintenance management systems.

LEARNING OBJECTIVES

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

- 1. Describe the major aspects of managing maintenance activities including management of maintenance, maintenance program development, planning, scheduling, performing maintenance, assessment and improvement.*
- 2. Describe the different approaches to maintenance including preventive and corrective.*
- 3. Describe how routine maintenance activities are planned, scheduled, and controlled.*
- 4. Describe the use of Gantt and PERT charts and the critical path method to schedule major maintenance activities.*
- 5. Describe the steps involved in preparing for and conducting a pressure vessel inspection.*
- 6. Describe the use of computerized systems in managing maintenance, including a work order system.*
- 7. Describe various methods of monitoring equipment, including log sheets and trending.*
- 8. Describe the steps involved in developing a plant budget and controlling maintenance costs.*



OBJECTIVE 1

Describe the major aspects of managing maintenance activities including management of maintenance, maintenance program development, planning, scheduling, performing maintenance, assessment and improvement.

INTRODUCTION

Proper maintenance is a critical factor in the successful operation of all types of equipment. In addition to good execution of maintenance tasks, it is also important to understand other aspects of maintenance management. If these aspects are not considered, it is likely that the actual maintenance will not be effectively or efficiently carried out. This module provides an overview of these aspects so that a successful maintenance management program can be set up.

DEFINITION OF MAINTENANCE

The first thing to consider is the definition of maintenance.

The International Electrotechnical Commission (IEC), in their International Electrotechnical Vocabulary, describes maintenance as “The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.”

This definition has a number of components:

- **item:** This term includes all hardware and associated software such as equipment, components, devices, systems, and other physical assets.
- **perform a required function:** Maintenance is concerned with ensuring that equipment can perform required functions. These functions are a combination of design (which defines the limits of use) and operation (which describes its actual use).
- **to retain an item in, or restore it, to a state:** The purpose of maintenance is either to perform actions that keep equipment performing as required by doing preventive maintenance (to retain), or to repair it when it has failed by doing corrective maintenance (to restore).
- **combination of all technical and administrative actions, including supervision action:** Maintenance is not only the execution of maintenance tasks, but also administrative actions (such as planning and scheduling) and supervisory actions (such as hiring and training skilled personnel).

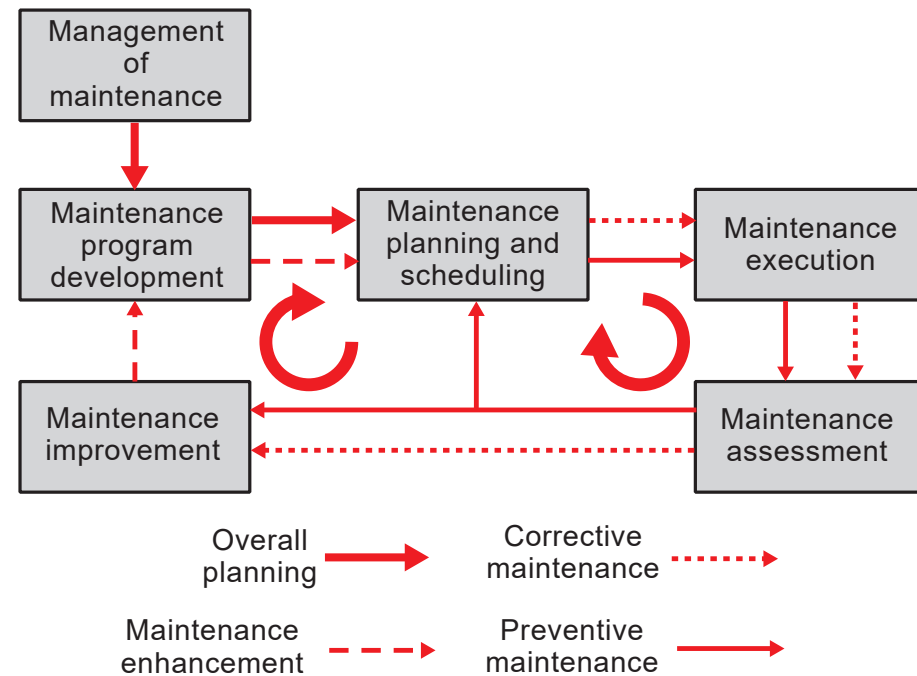
MAJOR ASPECTS OF MAINTENANCE MANAGEMENT

Figure 1 shows the major aspects of maintenance. Each aspect includes a number of processes that are carried out by different people involved in maintenance.

These processes can be divided into four categories:

- **Overall planning:** includes management of maintenance, maintenance program development, and maintenance planning and scheduling.
- **Preventive maintenance:** includes maintenance planning and scheduling, maintenance execution, maintenance assessment, and maintenance improvement.
- **Corrective maintenance:** includes maintenance planning and scheduling, maintenance execution, maintenance assessment, and maintenance improvement.
- **Maintenance enhancement:** includes maintenance improvement, maintenance program development, and maintenance planning and scheduling.

Figure 1 – Major Aspects of Maintenance



(Courtesy of Strategic Maintenance Solutions Inc.)

Management of maintenance is the responsibility of supervisors and managers, and includes:

- Developing a high-level maintenance strategy for an organization
- Managing, coordinating, and supervising maintenance groups
- Providing finances and managing maintenance budgets
- Providing resources for maintenance, such as skilled staff, spare parts and materials, maintenance facilities, tools and support equipment, and manual and computerized information systems

Maintenance program development is the responsibility of maintenance planners, with involvement from maintenance personnel, and includes:

- Identifying preventive maintenance tasks
- Determining support resources needed for preventive maintenance tasks



Maintenance planning and scheduling is the responsibility of maintenance planners, and includes:

- Planning resources needed to carry out specific preventive and corrective maintenance tasks
- Scheduling maintenance tasks within the limits of available resources

Maintenance execution is performed by maintenance staff and includes:

- Obtaining resources such as spare parts and specialized tools
- Traveling to the work site
- Following safety and environmental procedures
- Dismantling, repairing, and reassembling equipment
- Investigating and diagnosing failures
- Documenting the results of work done and resources used

Maintenance assessment is a responsibility shared by maintenance planners and maintenance personnel, and includes:

- Assessing and documenting the success of maintenance actions
- Measuring maintenance performance indicators
- Performing failure analysis, especially for major failures
- Assessing equipment availability, reliability, and cost
- Reviewing the success of preventive maintenance programs

Maintenance improvement involves not only maintenance staff, but may also involve other groups such as design engineering, and could result in:

- Design improvements or modifications
- Changes to operating procedures
- Changes to maintenance procedures
- Improvements to preventive maintenance tasks and resources

Two process loops are shown in Figure 1. The first one (on the right) is the maintenance cycle. This cycle takes place constantly as maintenance tasks are identified or triggered, planned, scheduled, executed, and assessed. The second loop (on the left) is the continuous improvement loop; it deals with incorporating changes and improvements in equipment, procedures, and tasks. Management of maintenance is also an ongoing activity although it is not involved in a cycle.

MAINTENANCE AND RELIABILITY

It is worthwhile noting that maintenance and reliability are closely related. Reliability starts with equipment that has been designed for the required operating conditions and performance. It must also be operated within design limits and according to specified operating procedures. Finally, the required maintenance has to be carried out. All three factors are necessary to achieve reliability.

Reliability can be used to measure the success of a maintenance program. However, it is not the only factor to consider since measures such as availability, product quality, production capacity, and cost may be equally, or even more, important.

OBJECTIVE 2

Describe the different approaches to maintenance including preventive and corrective.

APPROACHES TO MAINTENANCE

There are different approaches to managing maintenance. Methods and terminology are not entirely standard. Whereas some refer to 'maintenance management', others use the term 'asset management', or even the combined term 'maintenance and reliability'. Even though people use different approaches, the key concepts are the same.

Total Productive Maintenance (TPM) is a well-known formal approach to maintenance management. It was developed in Japan as part of the quality movement and uses a structured approach to ensure reliability and develop a standardized maintenance program. It applies to all aspects of maintenance. It is appropriate if a company wants a structured and formal means of improving maintenance and reliability. However, if there are known areas that need improvement, it may be more effective to address these areas individually rather than following a comprehensive method such as TPM.

Other approaches to maintenance management focus on risk management. These approaches include: Reliability Centered Maintenance, Risk-Based Inspection, and statistical risk assessment.

This module does not specifically recommend any of these approaches, but instead focuses on basic methods and procedures.

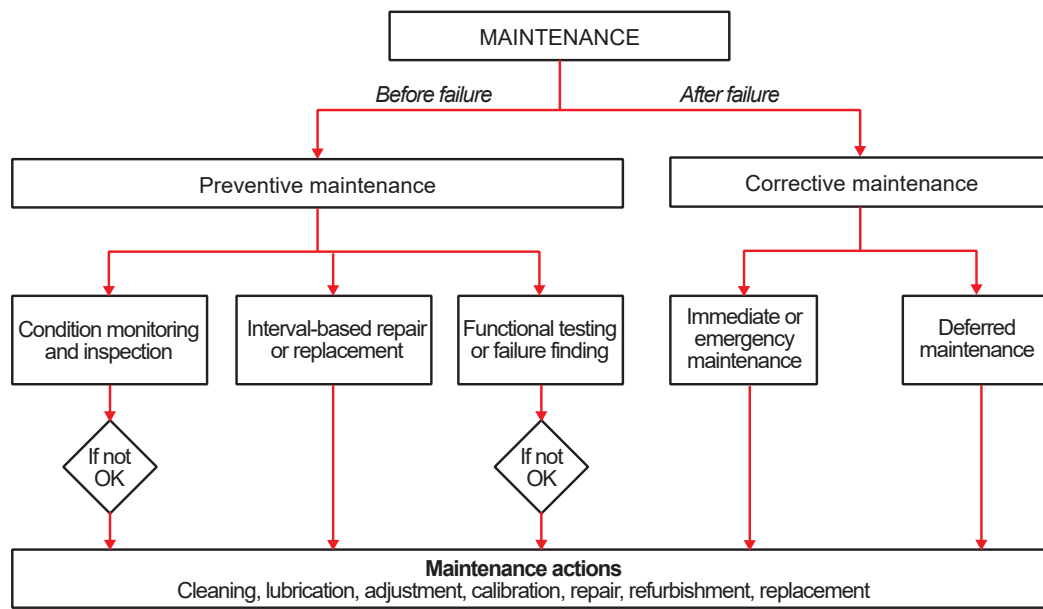
TYPES OF MAINTENANCE

There are two major categories of maintenance: preventive and corrective.

The International Electrotechnical Commission (IEC), in their International Electrotechnical Vocabulary, describes **preventive maintenance** as "The maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item."

The IEC vocabulary also describes **corrective maintenance**: "The maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function."

Preventive maintenance covers all pre-planned maintenance activities. There are various approaches, but preventive maintenance is always performed before failure occurs. On the other hand, corrective maintenance is done only after a failure. A further breakdown of these two types of maintenance is shown in Figure 2.


Figure 2 – Types of Maintenance Tasks


(Courtesy of Strategic Maintenance Solutions Inc.)

Preventive Maintenance

Preventive maintenance can be broken down into three types of maintenance:

- Condition monitoring and inspection
- Functional testing or failure finding
- Interval-based repair or replacement

Corrective maintenance is carried out only after failure has occurred. In some cases, for example, redundant equipment, it may be possible to defer the maintenance until a more appropriate time. If corrective maintenance has to be done immediately, it is often called **emergency maintenance**.

Condition Monitoring

This type of maintenance is also commonly referred to as predictive or condition-based maintenance.

Since even the same equipment often fails at different intervals, the most efficient time to perform maintenance is just before failure. This is possible only if there is a good way to monitor the equipment, and if it is a convenient time to do the maintenance. For example, if you are monitoring engine condition on an aircraft, you want to have enough time to get to your destination, or at least find a landing spot.

Examples of condition monitoring are:

- Monitoring oil filter differential pressure and replacing the filter when a pre-determined pressure is reached.
- Inspecting a pressure vessel for corrosion or erosion by visual inspection, or by measuring wall thickness using ultrasonic inspection.
- Performing oil analysis and replacing the oil when certain levels of contaminants are reached.
- Doing vibration monitoring on rotating equipment, such as a pump, and replacing it when the vibration exceeds a certain value.
- Using human senses to detect changes in sound, oil leakage, or other signs of deterioration.

Functional Testing

Functional testing, also called “failure finding”, is aimed at finding hidden failures. A hidden failure is one that does not become evident when it occurs because the function is not required at that time, or is only activated intermittently. The failure becomes evident when the function is activated, at which point, there may be undesirable consequences. Failure finding is especially relevant for protective devices that are not needed very often. However, if they fail to operate when required, the results may be catastrophic.

Examples of failure finding tasks are:

- Checking an overspeed switch to make sure it trips at the correct speed
- Verifying the correct operation of a pressure switch
- Starting a backup generator on a monthly basis to verify its operation
- Exercising shutoff valves to prevent them from seizing up
- Checking the spare tire on your car

Interval-based Maintenance

Interval-based maintenance entails regular repair or replacement of components or equipment after a specified interval has passed, without regard for equipment condition or performance. The interval can be elapsed (calendar) time, running hours, number of operating cycles, number of starts, distance, or any other relevant factor.

Interval-based maintenance is normally chosen when condition monitoring is not cost-effective, or, for example, when it is more convenient to do the repair or replacement in conjunction with another activity, such as a yearly shutdown of the whole plant.

Examples of interval-based maintenance are:

- Replacing an oil filter after 6000 km
- Overhauling a pump every two years
- Replacing turbine blades after 100,000 running hours
- Repairing a starter after 500 starts

Corrective Maintenance

Corrective maintenance is also called reactive or breakdown maintenance. If the failure has a major impact on production or operation, it will likely become the highest priority. If the impact is small and backup equipment is available, it may be possible to defer the maintenance until a more convenient time.

A good maintenance program should prevent most major failures. However, it may not be worthwhile to try to avoid every failure. It is quite possible to spend more money on expensive condition monitoring techniques, or to replace equipment that is still in good condition, than it would if you waited until failure occurred. Clearly, waiting is not acceptable for failures that could result in major safety hazards or large financial losses.



OBJECTIVE 3

Describe how routine maintenance activities are planned, scheduled, and controlled.

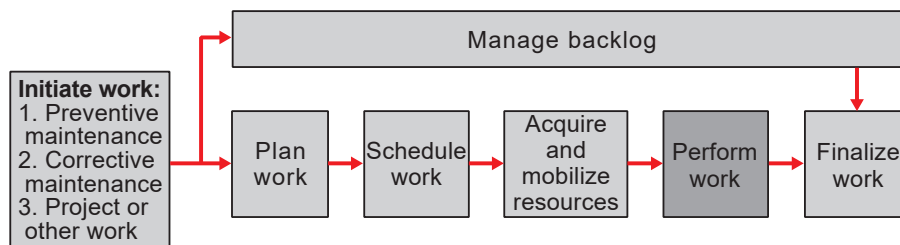
PLANNING AND SCHEDULING PROCESS

Effective planning and scheduling is crucial to the success of a maintenance program. It reduces the number and frequency of maintenance activities, which in turn eliminates delays in the production schedule, and improves task planning.

Benefits include:

- Reduced downtime and impact on production schedules
- Reduced time required to do the work
- Reduced maintenance costs (often by 10% to 30%)
- Reduced environmental impact
- Improved regulatory compliance
- Improved utilization of resources (such as personnel, parts/materials, and tools/work equipment/vehicles)
- Improved measurement of maintenance performance
- Improved personnel safety

Figure 3 – Planning and Scheduling Process



(Courtesy of Strategic Maintenance Solutions Inc.)

The first step is to initiate the work which is usually done by raising a work request. For preventive maintenance (a repetitive activity), this is often triggered automatically by a computer system. The work request moves immediately to the planning stage. Corrective maintenance usually starts with a manual work request raised by operations, or possibly maintenance or another group that reports a failure or identifies unplanned work that needs to be done. These work requests should be screened and approved before they are passed to the planning stage. A third type of work request is issued for project work or miscellaneous tasks.

Following Figure 3 to the second step, planning involves identifying required resources.

The scheduling step is concerned with deciding the most appropriate time for the work to be carried out. At this point, the work request is turned into a work order. The next step is acquiring and mobilizing resources. This usually involves:

- Obtaining parts and materials (from inventory or by purchase)
- Reserving specialized tools and support equipment
- Identifying who will do the work
- Transporting resources (including maintenance staff) to the work location

Then, the maintenance work is carried out.

Finalizing the work includes documenting the results on the work order and returning tools and support equipment, as well as unused parts and materials, to inventory.

During this process, the total amount of work yet to be completed, commonly referred to as the backlog, is managed and adjusted in response to changes in priorities, the addition of new corrective work, and other unforeseen factors.

Maintenance Planning

In the planning stage, the planner identifies all resources that are going to be needed to complete the maintenance tasks. The planned activities may range from quite small to very large. An average maintenance activity requires a small number of staff, a few parts and materials, and can be completed in four to eight hours. Major maintenance activities are usually performed during a major plant turnaround or shutdown (both terms are used). In general, the items that have to be planned for both minor and major maintenance activities are similar, but differ in magnitude.

Planning is needed to identify some or all of the following items:

- Description of tasks to be performed and their sequence (if important)
- Length of downtime required (equipment, system, or plant)
- Number of staff and hours needed for each type of maintenance trade or specialty
- Types of spare parts and materials and where they are to be sourced (inventory or purchase)
- Specialized tools and support equipment
- Lifting equipment (e.g. a crane)
- Special safety and environmental procedures
- Special maintenance procedures
- External contractors and services
- Financial account codes to which the costs are to be charged
- Cost breakdown and total cost for the task

Normally, these resources are added to the work order, which can be either a paper form or an electronic form linked to a computer database. The use of a computer system to manage maintenance, which is becoming very common, is described in Objective 6.

For preventive maintenance tasks, since the required resources have usually been previously identified, the planning process is very quick. In some cases, it can be done automatically by the computer system. For corrective maintenance tasks, the planning process has to be done for each individual task.



Maintenance Scheduling

Scheduling occurs after planning is completed. Scheduling consists of deciding when tasks should be done.

The actual time it takes to complete a task depends on:

- How urgent the task is (priority)
- When the equipment can be shutdown
- When required material resources, such as spare parts, can be acquired
- When labour resources are available

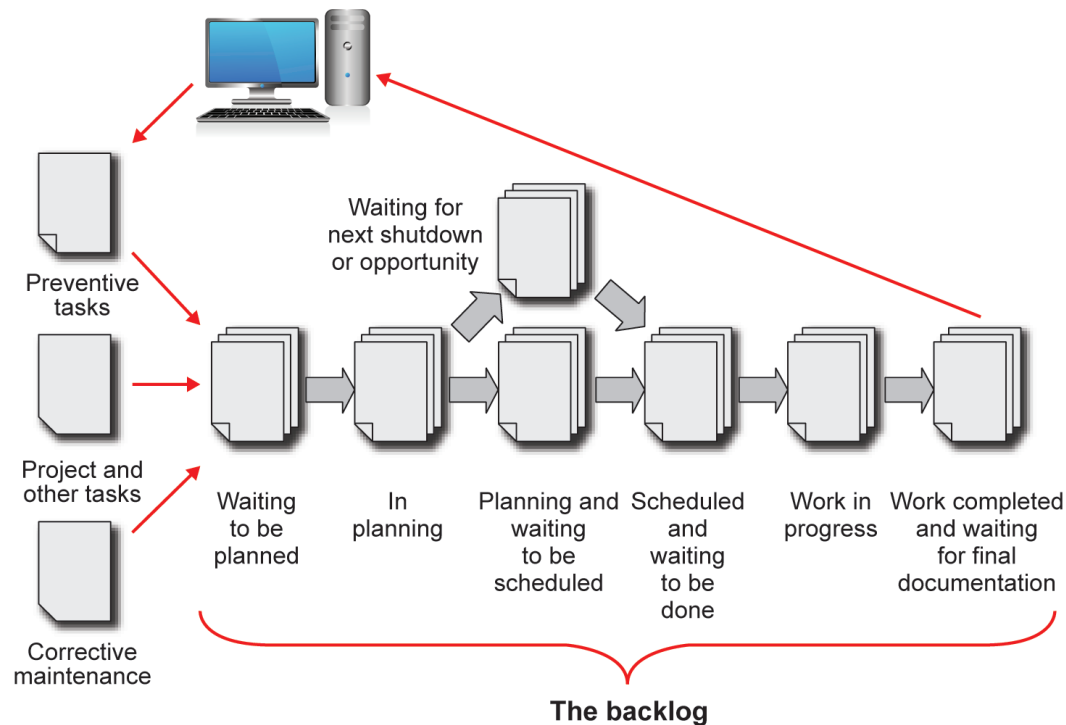
The planner tries to make the most efficient use of all resources, especially maintenance staff, and also tries to reduce downtime by scheduling tasks on the same equipment or system at the same time. If the maintenance work involves dependent (interrelated) tasks, more extensive scheduling techniques are used. These are described in the next objective. Most routine maintenance tasks are independent. A planner assigns a certain number of preventive maintenance tasks to various maintenance staff and crews, usually on a daily or sometimes on a weekly basis.

Corrective maintenance tasks can be a challenge to the scheduling process. They occur unexpectedly and result in the deferral of preventive maintenance and other planned tasks. It is important to determine whether corrective maintenance is of an emergency nature, and therefore has to be responded to immediately, or whether it can be deferred until a more appropriate time.

The Maintenance Backlog

The list of all maintenance tasks that have been initiated, regardless of the stage they are at, is referred to as the backlog. Figure 4 shows the stages of the backlog and illustrates how work requests and work orders progress through the stages.

Figure 4 – The Maintenance Backlog



(Courtesy of Strategic Maintenance Solutions Inc.)

A major function of the planning process is to manage the backlog. Because tasks take time to move through the various stages, the backlog will never be zero. An average backlog represents about three weeks of work. If the backlog becomes too large, this is a good indication that there are not enough resources available to complete all of the work, and it is likely that some work is not being done when required.

MAJOR MAINTENANCE SHUTDOWNS

The most intensive and time-consuming planning and scheduling activities occur when there is a major shutdown of a facility (turnaround). The planning steps are essentially the same as those described earlier, except that they are done simultaneously for a significant number of tasks. Because one of the goals is to minimize total shutdown time, the scheduling process is more complicated. The techniques described in the following objective address how to schedule tasks for a major shutdown. Briefly, a major shutdown requires detailed planning and scheduling to:

- Meet downtime, cost, and other objectives
- Isolate and deactivate entire systems
- Ensure a proper and safe shutdown
- Manage the special safety procedures required by the amount and type of work
- Ensure safe and timely startup of the plant



OBJECTIVE 4

Describe the use of Gantt and PERT charts and the critical path method to schedule major maintenance activities.

PREPARING A SCHEDULE

The purpose of scheduling is to accomplish a set of tasks in the most efficient manner within existing constraints in order to meet certain objectives. The tasks that require scheduling are normally dependent on each other in some way, and therefore have to be organized in a logical and time-efficient manner. Constraints, such as the amount of personnel available, always exist and have to be considered during the scheduling process. For major activities, management usually provides overall objectives such as cost or shutdown limits.

Scheduling involves a series of steps that are normally done in the following order:

1. Identify all required tasks
2. Estimate the duration of each task
3. Identify required resources (such as trade type, hours, materials, parts, tools, and work equipment)
4. Organize tasks into a logical order and determine dependencies between tasks
5. Apply resource and other constraints
6. Review the critical path and adjust resources as needed to meet planned deadlines
7. Estimate final cost and shutdown duration
8. Make tradeoffs as needed

Scheduling Concepts

The first consideration in scheduling is to understand what information is needed. Figure 5 shows one method of recording the time-related data that has to be determined for each task.

The first step is to fill in the task description and estimate the duration of the task. The other fields record relevant timing information that can be filled in as the tasks are scheduled. They are:

- **Early Start:** the earliest time that the task can be started. This may depend on the timing of related tasks.
- **Early Finish:** the earliest time that the task can be completed. This is determined by adding the early start time to the duration.
- **Late Finish:** the latest time that the task can be completed without impacting overall completion time.
- **Late Start:** the latest time that the task can be started without delaying the overall completion time. This is calculated by subtracting the duration from the late finish time.
- **Slack:** the amount of time a task can be delayed after the early start time without impacting overall completion time.

Figure 5 – Data Required for Scheduling a Task

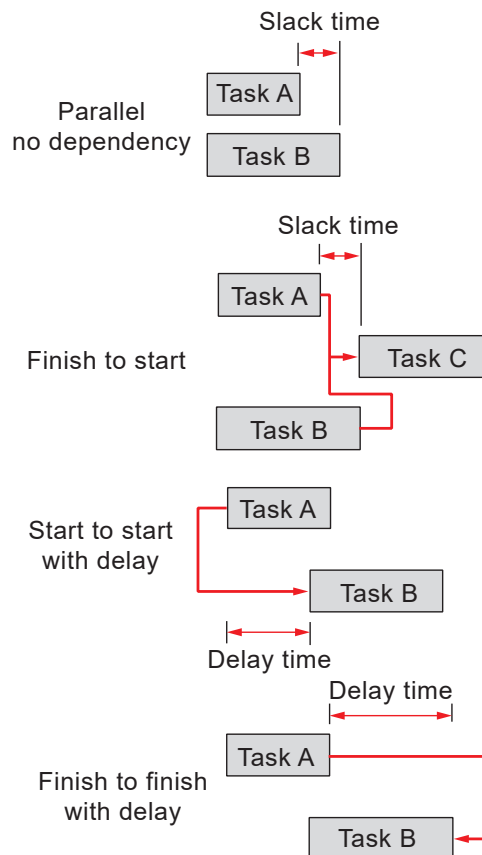
Early Start	Duration	Early Finish
Task Name		
Late Start	Slack	Late Finish

(Courtesy of) Strategic Maintenance Solutions Inc.)

To calculate these times, the planner has to determine task dependencies. Figure 6 shows several possible dependencies:

- **Parallel (no dependency):** the two tasks are independent. The shortest completion time is achieved by doing them in parallel, as long as sufficient resources are available. Note that the shorter task can be started later by an amount of time equal to the difference between the two duration times (the slack time).
- **Finish to start:** Task C cannot be started until Task B has been completed. Again, there is slack time for Task A.
- **Start to start with delay:** Task B cannot be started until after a delay following the start of Task A.
- **Finish to finish with delay:** Task B cannot be finished until after a delay following the finish of Task A.

Of these dependencies, the first two are the most common.

Figure 6 – Task Dependencies


(Courtesy of) Strategic Maintenance Solutions Inc.)



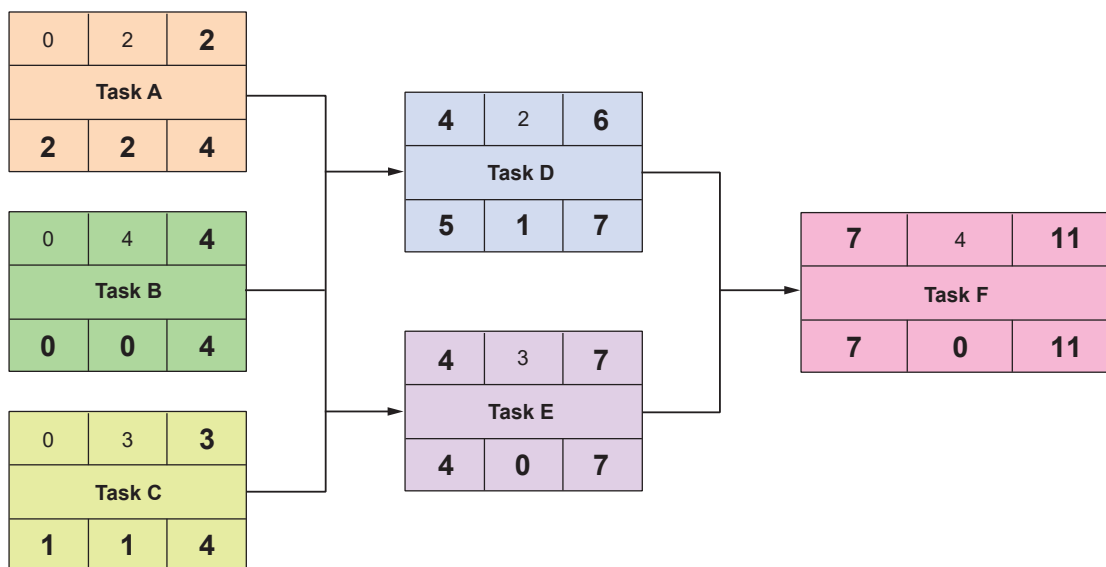
PERT CHARTS

Using the format shown in Figure 5, it is possible to organize the tasks into a schedule. A simple example is shown in Figure 7. This type of diagram is referred to as a PERT (Program Evaluation and Review Technique) chart. The numbers in the example are measured in days, but other times can be used. To fill in the task times (shown in bold), the following steps are carried out for each set of parallel tasks:

1. The early start time is 0 for the first set of parallel tasks (tasks A to C).
2. The early finish time is filled in for each task by adding the duration to the early start time.
3. The late finish time is the same for all parallel tasks and is determined by adding the longest duration (4 days) to the early start time (0).
4. The late start time is calculated for each task by subtracting the duration from the late finish time.
5. Finally, the slack time is calculated by subtracting the early start from the late start time.

Unless a delay is required before the next set of parallel tasks begins (tasks D and E), the early start time is equal to the late finish time of the previous set of parallel tasks.

Figure 7 – PERT Chart

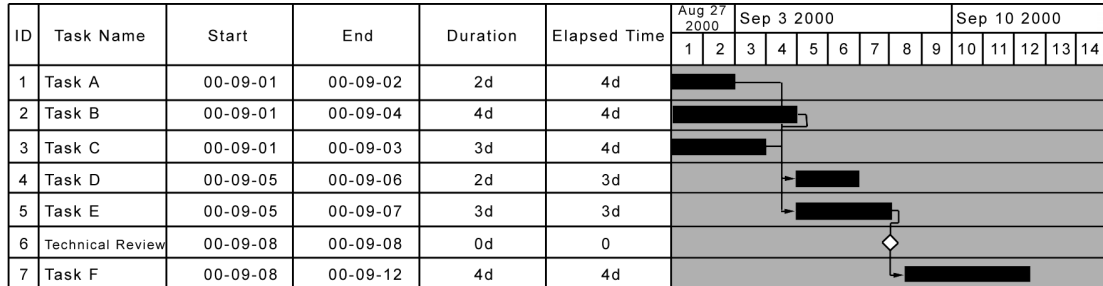


(Courtesy of Maintenance Solutions Inc.)

GANTT CHARTS

If the tasks are placed on a timeline, the result is a Gantt chart. Figure 8 shows an equivalent Gantt chart for the PERT chart in Figure 7. Gantt charts are named for Henry Gantt, who developed this concept in the early 1900's.

Figure 8 – Gantt Chart



(Courtesy of Strategic Maintenance Solutions Inc.)

The strong point of a Gantt chart is its ability to clearly display overall progress. Figure 8 also shows how a specific milestone, such as a technical review, can be included in the timeline.

CRITICAL PATH

Both PERT and Gantt charts can be used to determine the **critical path**. This is defined as all the tasks that will increase project completion time if they take longer than planned. If there is some way to shorten the duration of any of these tasks, then the overall completion time will be decreased.

Once the schedule has been built, it is possible to calculate the total completion time using the tasks on the critical path. If there is a need to reduce the total completion time, then the only tasks that matter are those on the critical path. The slack time for tasks on the critical path is always zero. In Figure 7 and Figure 8, tasks B, E, and F form the critical path.

Once the project is under way, it is most important to focus on the tasks that are on the critical path. These are the ones that determine whether or not the project can be completed on schedule.



OBJECTIVE 5

Describe the steps involved in preparing for and conducting a pressure vessel inspection.

INTRODUCTION

The following example explains the general steps involved in planning and scheduling a pressure vessel inspection, including the replacement of a relief valve. It is for illustrative purposes only.

The process has been documented using Microsoft Project, but other project management software can also be used. This type of software is used because it allows for detailed scheduling of a project, including production of critical path flowcharts or Gantt charts, with very little time consumed.

TASK PREPARATION

The first step is to identify the tasks required to complete a pressure vessel inspection. It is important to consider not only the actual inspection tasks, but also safety requirements and preparation tasks.

One way to identify tasks is to group them by type into broad categories:

- Preparation
- Safety requirements
- Inspection
- Completion

Preparation includes these tasks:

- Obtain special tools (e.g. the device to do the ultrasonic inspection)
- Pick up spare parts (e.g. the replacement relief valve)
- Travel to the location of the pressure vessel (this may or may not be significant)

Safety requirements entail:

- Obtaining a work permit
- Isolating the pressure vessel and depressurizing it (done by an operator)
- Performing a safety check before putting the vessel back into service

The actual inspection involves:

- A thorough visual inspection of the vessel for corrosion or other signs of deterioration
- An ultrasonic inspection of wall thickness at predetermined points
- Replacement of the relief valve

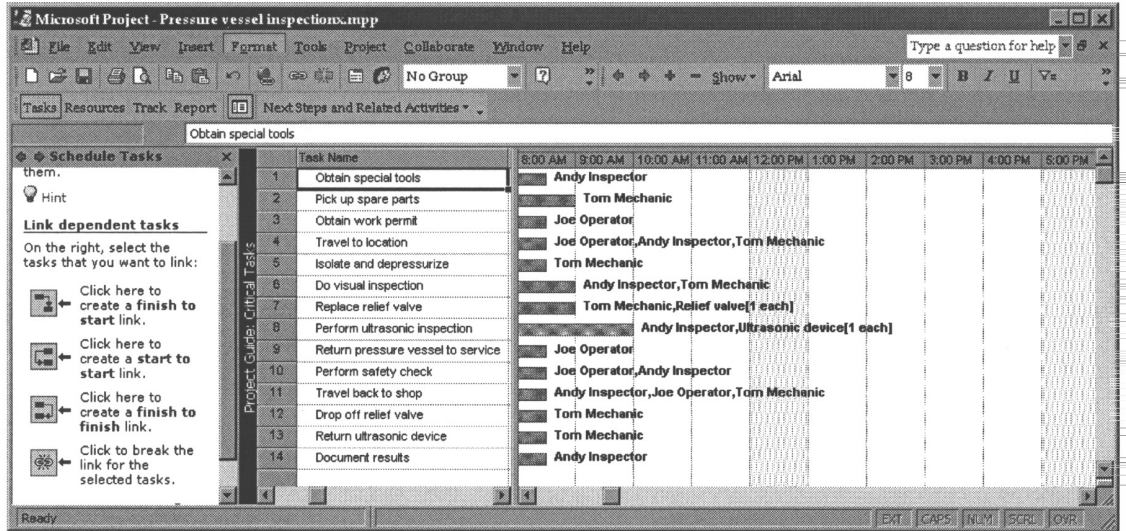
Completion includes:

- Returning the pressure vessel to service and verifying proper operation
- Returning the relief valve to the repair shop
- Traveling back to the maintenance shop
- Documenting the results on the work order and official inspection forms

There are three types of skill required: an operator, a technician or technologist who knows how to do the ultrasonic inspection, and a maintenance worker to replace the relief valve. The visual inspection can be done by a maintenance worker.

A list of the tasks and required resources is shown in Figure 9. This list is used to prepare the schedule.

Figure 9 – Initial Task with Resources



TASK SCHEDULING

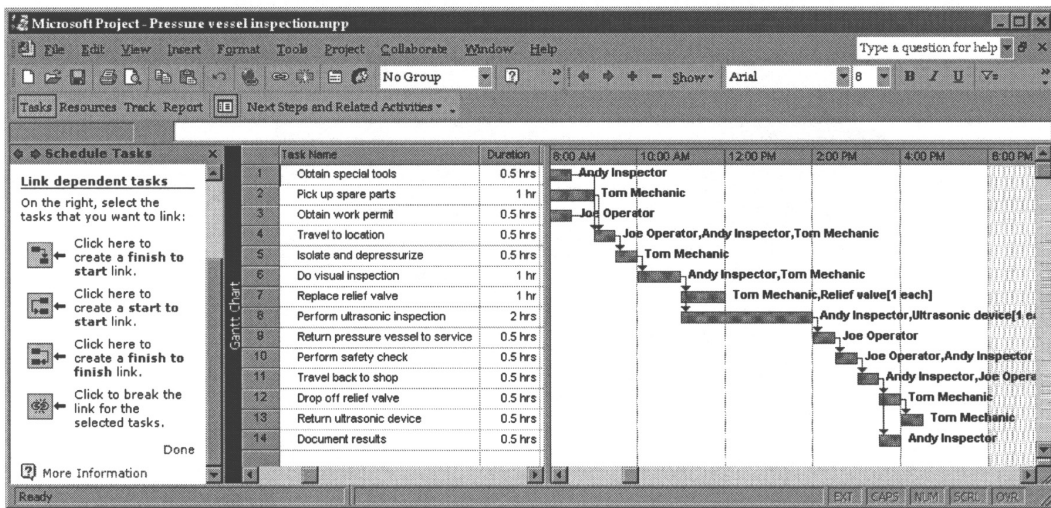
Then, the tasks are linked by adding the dependencies between them. As shown in Figure 9 and Figure 10, this is done in Microsoft Project by selecting two tasks, and then choosing the type of dependency from the panel on the left side of the screen. Where possible, tasks are left in parallel. However, the most common situation is to have one task start as soon as the previous one is finished.

In the pressure vessel inspection example, it is possible to perform the task with only an operator and one maintenance worker who is qualified to do ultrasonic inspections. With two workers, there are only two tasks that can be done in parallel — the operator can get the permit while the maintenance worker gets the parts. The total elapsed time is 9.5 hours with an equipment downtime of 5 hours.

However, if it is important to complete the task in the least amount of time, a third worker can be added so that more tasks can be done in parallel. This scenario is shown in Figure 10. The total elapsed time with 3 workers is 7.5 hours with an equipment downtime of 3 hours. This assumes that two workers do the visual inspection, and then do the ultrasonic inspection and relief valve replacement in parallel.



Figure 10 – Linking Dependent Tasks

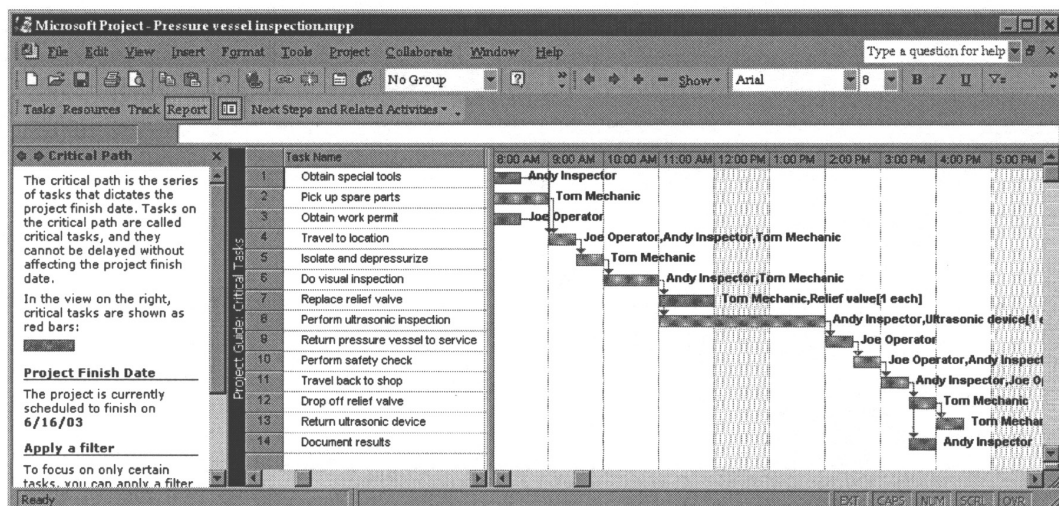


Critical Path

Most software highlights the critical path as shown in Figure 11. By analysing the critical path, it is possible to consider different scheduling options that may reduce the total elapsed time and make better use of available resources.

For the pressure vessel inspection example, a further time reduction is possible if Tom Mechanic performs both the visual inspection and relief valve replacement at the same time, while Andy Inspector performs the ultrasonic inspection. This reduces both the total elapsed time and equipment downtime by 1 hour.

Figure 11 – Gantt Chart Showing the Critical Path



OBJECTIVE 6

Describe the use of computerized systems in managing maintenance, including a work order system.

INTRODUCTION

Most companies use computerized information systems to assist with maintenance management. These systems are commonly referred to as Computerized Maintenance Management Systems (CMMS) or Enterprise Asset Management (EAM) systems. A large variety of software is available for purchase. Some systems are designed for small applications and can be run on a desktop computer. At the other end of the scale are server based systems for large corporations that can be accessed from anywhere on a network.

Most CMMS's have similar functionality which usually includes these major components:

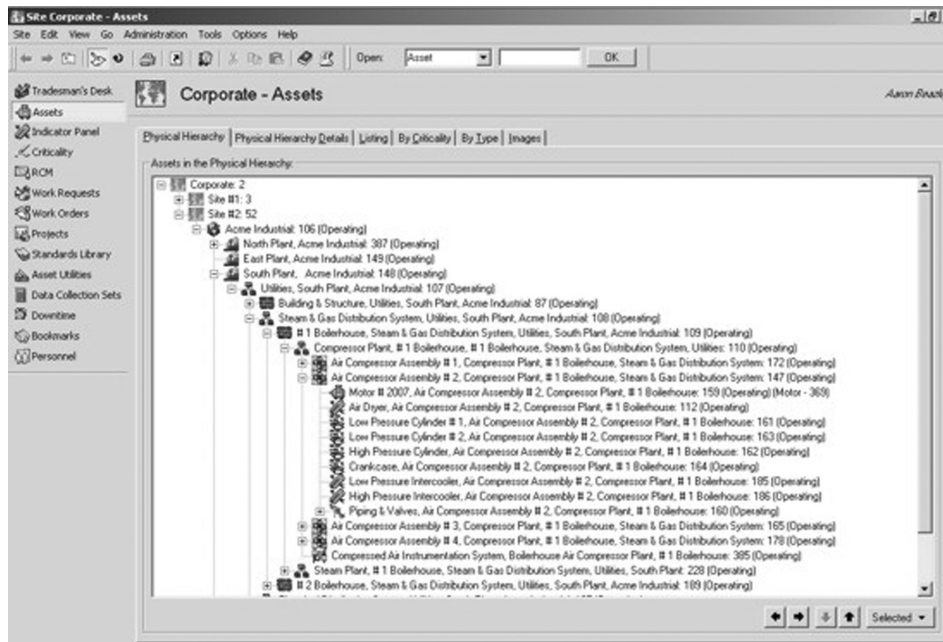
- Facility and equipment information
- Work management (work requests and work orders)
- Planning and scheduling
- Preventive maintenance
- Spare parts and materials
- Equipment tracking
- Analysis and reporting

FACILITY AND EQUIPMENT INFORMATION

The information contained in a CMMS can be used to organize facilities and equipment into a hierarchy as shown in Figure 12. This hierarchy organizes equipment information by location and makes it easier to find a specific piece of equipment.



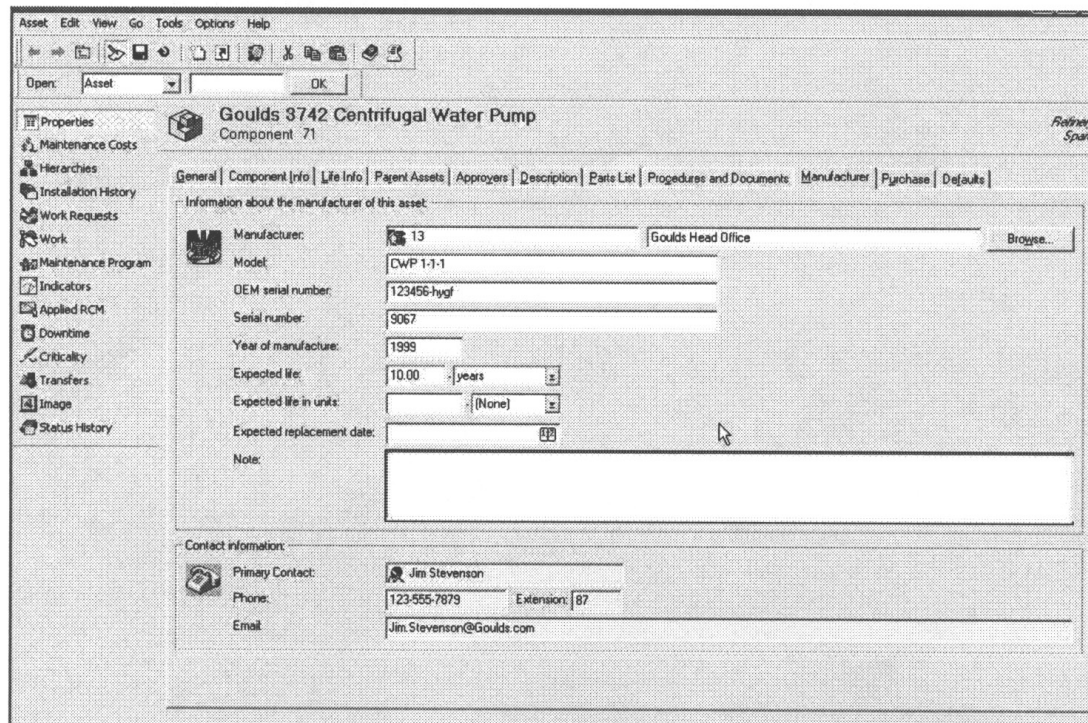
Figure 12 – Ivira EAM Example Screen Showing an Asset Hierarchy



(Courtesy of Ivira Corporation)

A wide variety of information can be recorded about the equipment including manufacturer data (e.g. manufacturer name, model number, and serial number) as shown in Figure 13. The tabs across the top of the screen show the different types of information available including: General, Component Info, Life Info, Parent Assets, Approvals, Description, Parts List, Procedures and Documents, Manufacturer, Purchase, and Defaults.

Figure 13 – Ivira EAM Example Screen Showing Equipment Manufacturer Data



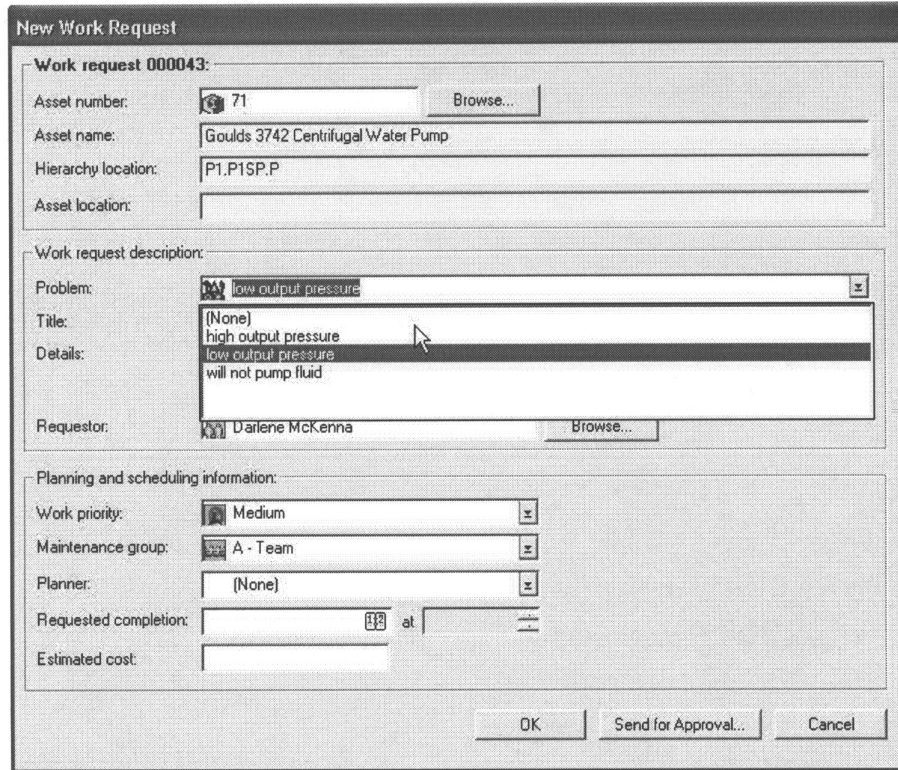
(Courtesy of Ivira Corporation)

WORK MANAGEMENT

Probably the most important function of a CMMS is the work management component. This supports the raising of work requests and processing of work orders. Work orders allow current work activities to be identified, approved, planned, scheduled, managed, and documented. Completed work orders document the maintenance history of the equipment and are critical for future analysis.

The work order process begins with the raising of a work request. Figure 14 shows a request to investigate a low pressure problem with a water pump.

Figure 14 – Ivara EAM Example Screen Showing a Work Request



New Work Request

Work request 000043:

Asset number: 71 Browse...

Asset name: Goulds 3742 Centrifugal Water Pump

Hierarchy location: P1.P1SP.P

Asset location:

Work request description:

Problem: low output pressure

Title: (None)

Details: high output pressure
low output pressure
will not pump fluid

Requestor: Darlene McKenna Browse...

Planning and scheduling information:

Work priority: Medium

Maintenance group: A - Team

Planner: (None)

Requested completion: 1/29 at 10:00

Estimated cost:

OK Send for Approval... Cancel

(Courtesy of Ivara Corporation)

Once the work request has been approved, it is turned into a work order which begins the planning and scheduling process (see Figure 15).



Figure 15 – Ivara EAM Example Screen Showing a Work Order

(Courtesy of Ivara Corporation)

PLANNING AND SCHEDULING

The work order is then planned, which means that resources, such as labour, parts and materials, are identified. Other planning information, such as task duration and planned start time, are added to the work order (see Figure 16).

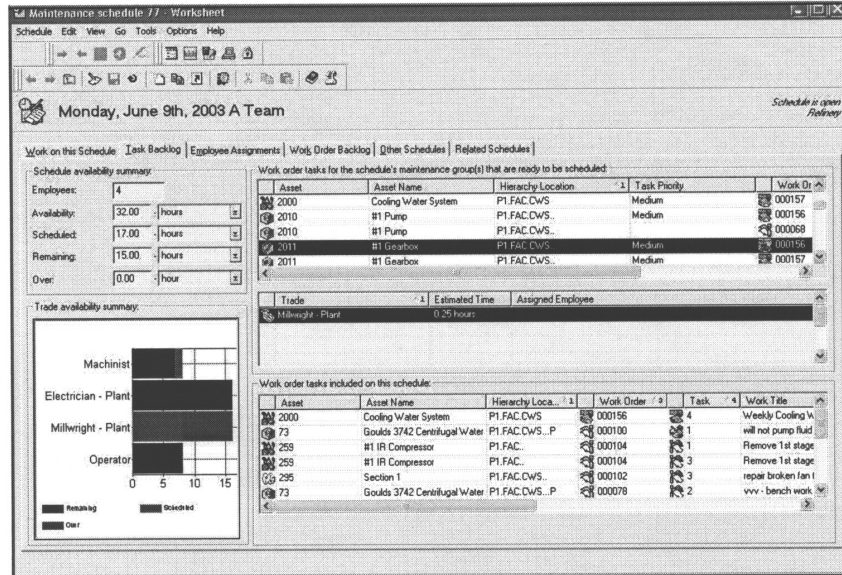
Figure 16 – Ivara EAM Example Screen Showing Work Order Planning

Type	Resource	Description	Quantity Required	Fulfillment Met	Assigned To	Demand Satisfied
Trade	Mechanical		2.00 hours	Maintenance	Scotty McLean	✓
Trade	Operator		2.00 hours	Maintenance		✓
Material	38	1" Mechanical Seal	1 each	Warehouse Issue		✓
Material	56	Gouds - High Strength Precision Shaft	1 each	Warehouse Issue		✓

(Courtesy of Ivara Corporation)

Then, all outstanding work orders are scheduled within the constraints of available labour and other required resources, such as parts and lifting equipment. Figure 17 illustrates the availability of labour resources with a bar graph for each type of trade and warns the planner when available labour has been exceeded.

Figure 17 – Ivira EAM Example Screen Showing work Orders Being Scheduled

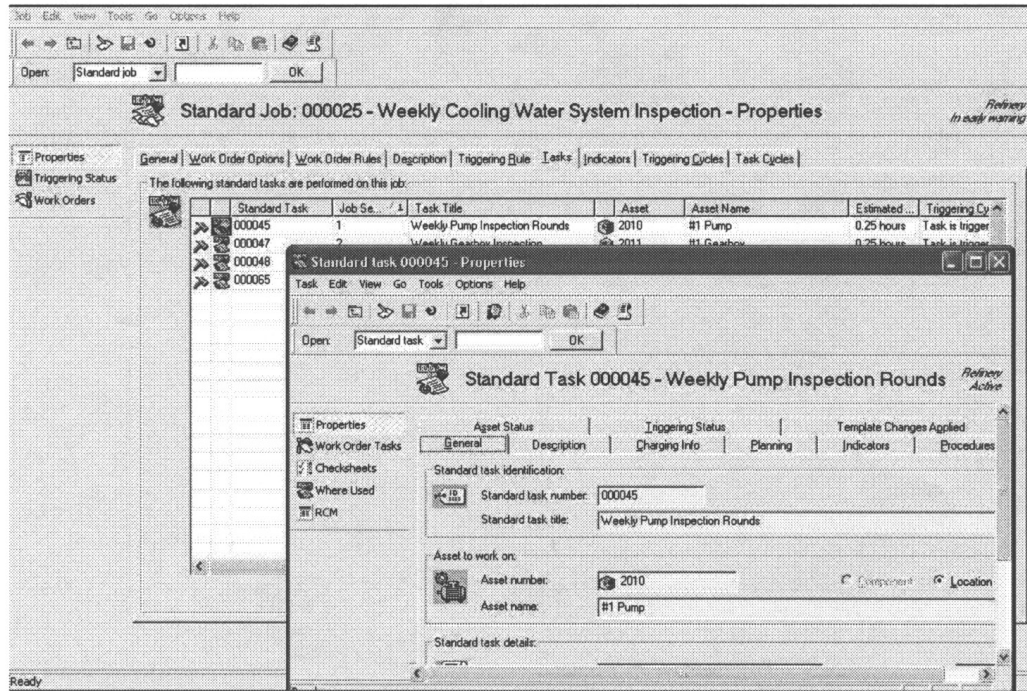


(Courtesy of Ivira Corporation)

When the work is completed, observations about the work and information about resources used are added to the work order, and then it is closed.

PREVENTATIVE MAINTENANCE

All preventive maintenance tasks should be recorded in the CMMS so that they can be pre-planned and automatically triggered to produce a work order. The screen shown in Figure 18 illustrates a standard task for a weekly inspection round.


Figure 18 – Ivira EAM Example Screen Showing Preventative Maintenance Tasks


(Courtesy of Ivira Corporation)

Work orders for preventive maintenance tasks can be triggered in various ways, including:

- Elapsed time at a fixed day or date (e.g. first Monday of every month)
- Elapsed time at a fixed interval (e.g. one month after the previous task)
- Running hours (e.g. every 8000 hours)
- When an indicator value is exceeded (e.g. pump pressure drops below 100 kPa)

SPARE PARTS AND MATERIALS

Availability of spare parts and materials is usually critical to the execution of a maintenance task. Some CMMS's contain a complete inventory and purchasing system, while others link to a separate system that handles purchasing and inventory control. Within the CMMS, spare parts and materials requirements are recorded for each piece of equipment and for each preventive task. This takes quite a bit of time to set up, but makes planning easier and faster.

EQUIPMENT TRACKING

Another useful function of a CMMS is equipment tracking. For example, when equipment, such as a pump or motor, is removed for repair, a replacement is installed from inventory and the repaired item is moved to inventory. It may be important to track the movement of equipment and to know where it is installed.

OBJECTIVE 7

Describe various methods of monitoring equipment, including log sheets and trending.

CONDITION MONITORING

Condition monitoring is an important component of maintenance. It consists of measuring relevant indicators of equipment condition that can be useful in predicting deterioration and the likelihood of failure. This knowledge is used to make decisions about the type of maintenance required.

There are a number of common techniques that break down into these categories:

- Vibration monitoring
- Oil analysis
- Thermography
- Ultrasonic inspection
- General monitoring (including equipment and process performance, output, pressures, and temperatures)

The first four techniques require specialized training and are beyond the scope of this objective. General monitoring is more common and is described below.

General Monitoring

General monitoring is often done manually using paper log sheets. Computerized monitoring program are also used. They gather data using portable hand-held data collectors or by monitoring control systems with permanently mounted sensors.

Figure 19 shows an example of a paper log sheet for monitoring an engine. The date and time of the entry and the hours on the run meter are recorded along with the name of the person who completed it. Each parameter is clearly described with its unit of measurement. Alert values are noted for each parameter where relevant. Where an alert value has been exceeded, the reading is circled.

The sequence of parameters on the log sheet is always an issue. For recording purposes, it is best to put them in the order that the readings are taken although this often differs between operators. When viewing the results, it is better to organize the readings logically according to systems and types of readings. The log sheet in Figure 19 is organized this way, but includes a separate column to indicate the normal input sequence (for reference purposes only).

Sometimes, a calculated value is required to recognize an abnormal condition. If the calculation is simple, such as the exhaust temperature spread shown in Figure 19, it can be added to the log sheet. This is the difference between the lowest and highest exhaust temperatures. If the spread is caused by an exhaust temperature that is too high, the engine may be receiving too much fuel through an eroded fuel nozzle. If the spread is caused by an exhaust temperature that is too low, there may be problems with a plugged fuel nozzle.

Everyone who logs equipment needs to be trained not only how to take readings, but also what they are used for, and what to do if an alert value is exceeded. If possible, the alert value readings should be documented separately from the log sheet by someone familiar with the engine and its operation.

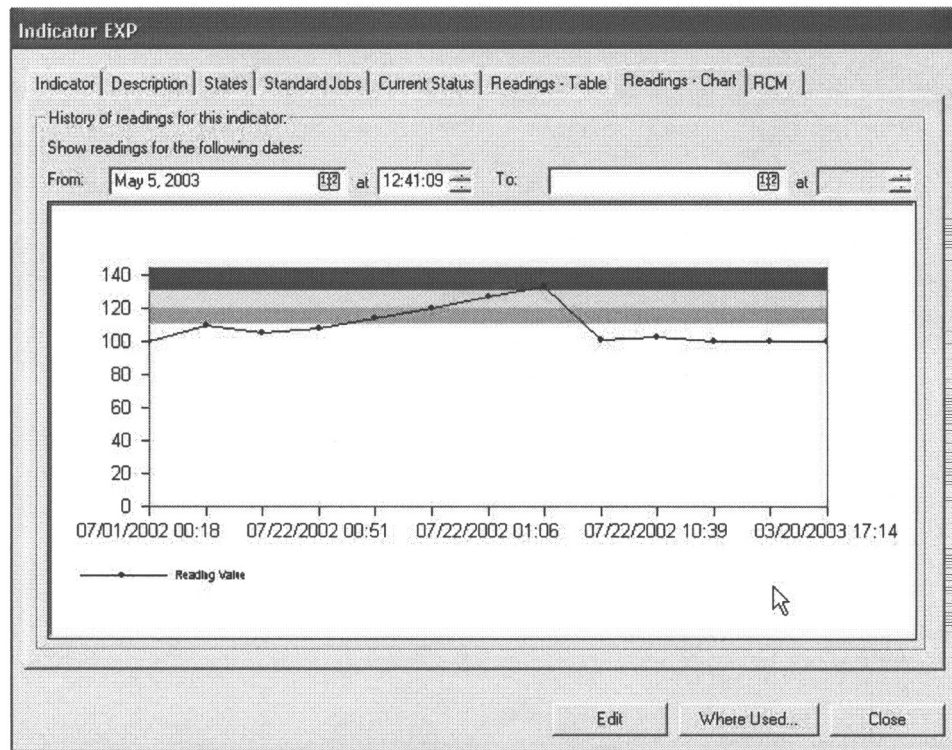


Figure 19 – Example of a Log Sheet (all numbers are fictitious)

Engine Log Sheet - Bears paw Unit 1							
Input Seq.	Parameter	Unit of Measurement	Low Alert	High Alert	Readings		
1	Name				A. Smith	A. Smith	P. Jones
2	Date	yy.mm.dd			03.06.01	03.06.02	03.06.03
3	Time	hh.mm			830	900	845
4	Run Hours	hrs			12 345	12 369	12 393
5	Ambient temperature	°C			21	16	18
6	Gas producer speed	RPM	8500	12 000	9200	9100	11 000
13	Power turbine speed	RPM	2000	7500	6100	6050	7000
16	Generator power	kW			16 300	16 000	15 900
15	Air filter diff pressure	mm H ₂ O		400	210	215	220
14	Compressor discharge pressure	kPa			254	243	298
17	Exhaust gas temp #1	°C		550	502	500	490
18	Exhaust gas temp #2	°C		550	503	585	571
19	Exhaust gas temp #3	°C		550	500	503	498
20	Exhaust gas temp #4	°C		550	498	507	502
21	Exhaust gas temp #5	°C		550	506	509	503
22	Exhaust gas temp #6	°C		550	508	501	510
23	Exhaust gas temp #7	°C		550	507	502	506
24	Exhaust gas temp #8	°C		550	506	504	503
Calc.	Temp spread	°C		80	10	85	81
8	Fuel pressure	kPa	200	350	320	330	360
10	Oil pressure	kPa	275	380	290	295	293
9	Oil temperature	°C	75	90	82	83	82
11	Oil filter diff pressure	kPa		100	60	62	63
12	Oil level	%	50		80	85	85
	Vibration - front	mm/sec		20	10	11	9
	Vibration - centre	mm/sec		20	12	14	13
	Vibration - rear	mm/sec		20	8	7	9
COMMENTS:							

The best way to monitor changes in condition is to display indicator values on a trend chart.

Some CMMS's include a condition monitoring feature that can automatically trigger maintenance tasks. An example is shown in Figure 20. Note the three different alert bands at the top of the graph that indicate a progression of importance from alert to alarm to danger.

Figure 20 – Example Screen Showing a Trend Graph


(Courtesy of Ivara Corporation)



OBJECTIVE 8

Describe the steps involved in developing a plant budget and controlling maintenance costs.

MAINTENANCE COSTS

Maintenance costs are a significant component of ownership costs and must be closely monitored. Various methods are used to monitor and evaluate maintenance costs, including:

- The maintenance budget which plans costs annually as part of the corporate budgeting process
- Evaluation and analysis of specific equipment and assets, often using a computerized maintenance management system
- An overall analysis of maintenance costs in comparison with industry benchmarks or other data

In this objective, the emphasis is on the maintenance budget since it is the most common approach to controlling maintenance costs.

CAPITAL AND OPERATING COSTS

Costs are normally divided into two categories: capital and operating. This is done for accounting and tax purposes. Capital items are assets that can be written off (depreciated) over time against income, while expenses are deducted directly from income as they are incurred.

The majority of maintenance costs will be included in the operating budget. These include labour costs, spare parts and materials, external contracts, travel expenses, equipment rentals, and contract services.

Although capital maintenance expenses are not common, some companies consider major tools and support equipment (e.g. over \$1,000), major equipment replacement (e.g. over \$10,000) and modifications (e.g. over \$1,000) to be capital items. In some cases, companies designate a major overhaul as a capital expense.

THE MAINTENANCE BUDGET

It is always necessary to plan for maintenance expenditures. This process is normally handled through the annual budget. Each department prepares an estimate (budget) of anticipated expenditures for the coming year for approval by management. The supervisor of each department is responsible for monitoring expenditures throughout the year and ensuring that budget limits are not exceeded.

Because maintenance departments deal with costs that are not always predictable, it is important to plan the budget carefully and for management to understand the constraints associated with the budget.

Two approaches are used for budgeting:

- **Zero-based budgeting:** budget amounts are determined by identifying and estimating all activities to be carried out. For maintenance budgets, this works well for routine and major inspections although it takes a considerable amount of time to prepare.
- **Historical budgeting:** costs are estimated based on past history with actual expenditures, usually those of the previous year. This is the most efficient way to budget for miscellaneous expenses and minor work, as well as unscheduled work due to failures.

In both cases, adjustments may have to be factored in for expected increases, for example inflation and salary increases.

The most difficult elements to estimate are unscheduled work and major failures. Some companies provide only a moderate allowance for these situations and explain the variance (the difference between the budgeted amount and the actual expenditure) as required. If management has problems with variances, it may be best to budget a larger amount for unscheduled maintenance (even though it might not be entirely used up every year).

Although the amounts will obviously vary with equipment type, application, and equipment age, it has been found that yearly maintenance costs average about 3% to 6% of the total replacement value of equipment. For example, the yearly maintenance budget for a small facility worth \$10 million should be between \$300,000 and \$600,000.

Cost Reporting

Every company has its own cost structure which is represented by a series of account codes to which costs are charged. In general, maintenance costs can be divided into these categories:

- Internal labour (regular time plus overtime)
- Contract labour
- Spare parts and materials
- Supplies (such as lubricants)
- External services
- Company overhead charges

Cost reports are produced monthly and provided to the appropriate supervisors for review. These reports usually provide costs by account code as monthly and year-to-date totals. The reports should also show the budget amounts for each account code and the variance between budget and actual. The supervisor can then evaluate the actual costs against the budget amounts and identify significant variances. Variances can be divided into two types:

- **Permanent variances.** These are unexpected differences (such as costs related to a major failure), that increase the total annual maintenance expenditure.
- **Temporary variances.** These exist because of timing differences. For example, if a major inspection is done earlier than planned, an expense will be incurred earlier than budgeted. Temporary variances will not increase the total annual maintenance expenditure.

EQUIPMENT MAINTENANCE COSTS

Since the maintenance budget is based on costs associated with individual departments, it is not an appropriate tool for analyzing and understanding the actual costs associated with specific equipment. To do this, it is necessary to use the history contained in a CMMS. This history is built from costs associated with work orders that apply directly to the equipment. Thus, it is possible to analyze maintenance information by looking at the actual costs incurred to maintain one type of equipment, such as a pump, and compare individual costs against the average.



CHAPTER QUESTIONS

1. Identify and describe three components of the definition of maintenance.
2. Explain the difference between preventive and corrective maintenance.
3. List four items that could be identified during planning of maintenance.
4. Describe what is meant by the critical path.
5. List four types of information that might be recorded in a CMMS.
6. What are the two approaches used for preparing a maintenance budget?





CHAPTER 7

Safety

LEARNING OUTCOME

When you complete this chapter you should be able to:

Explain the components and application of safety programs, safety audits, and safety training.

LEARNING OBJECTIVES

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

1. *Describe the elements of a comprehensive safety program for a power plant.*
2. *Explain the purpose of and the process used for safety checklists, inspections, audits and reviews.*
3. *Explain the purpose of and the process used for safety orientation, education, and training.*



OBJECTIVE 1

Describe the elements of a comprehensive safety program for a power plant.

INTRODUCTION

The health and safety of all persons working at a power plant is of paramount importance. Protecting the health and safety of workers positively affects the reputation of the company. It negatively impacts how all stakeholders, employees, neighbours, media, governments and shareholders perceive the company.

Provision of the necessary safeguards and safety programs generates good health and safety performance: freedom from fatalities, injuries, and property damage. This will eliminate the need for the regulatory authority to take legal action.

Implementation of a comprehensive health and safety program requires the commitment of both human and financial resources but it is expected to more than pay for itself. This view is endorsed in a survey of U.S. business executives, “The Executive Survey of Workplace Safety” conducted by the Liberty Mutual Group, the leading provider of workers’ compensation insurance in the U.S.A.

Most business executives reported that workplace safety has a positive impact on a company’s financial performance.

Maintaining and improving workplace health and safety takes a lot of work, perseverance and effort. Just like production and quality improvement, it requires a process and a commitment to action on the part of all employees. There are safety proponents who place most of their emphasis on the process while others place emphasis on ensuring the right safety-related behaviour. Both of these major elements are required if exceptional safety performance is to be achieved.

A well-designed health and safety program is a must. It is the only way to control risks. However, the best process in the world is no good if there is unwillingness on the part of employees to follow it through personal action. This commitment is encouraged and achieved if good consultation and communication processes are in place and employees are given the right tools to perform their work safely.

Process and behaviour related safety improvements are not mutually exclusive. A health and safety program includes the elements necessary to obtain commitment to good safety behaviour.

HEALTH AND SAFETY PROGRAMS AND PROCESSES

There are a number of comprehensive health and safety programs or processes available which companies can use as a basis for developing their own programs. Information can be obtained from the following:

- Provincial workplace insurance boards and safety associations
- Canadian Centre for Occupational Health & Safety (CCOHS)
- U.S. Occupational Safety & Health Agency (OSHA)
- Other safety and standards organizations

The British Standards Institute (BSI) has taken the initiative to adopt a worldwide health and safety management system that is similar in process and functionality to the ISO 9000 quality control standard and to the ISO 14000 environmental management standard. Their BSI - OHSAS 18001: 1999 “Occupational Health and Safety Management System – Specification” is based on the British Standard BS 8800 but is rewritten in a format and in language that is similar to ISO 9000 and ISO 14000. This will ease implementation for companies already accredited to either ISO 9000 or ISO 14000 or both because it allows all the management systems to be integrated.

For a company or facility to develop, implement and maintain a fully functional safety program that adds real value to all onsite individuals requires the following:

- Commitment from top management
- Clearly stated health and safety policy
- Identification of hazards at the workplace
- Development of processes and procedures to control the risks
- Effective training of workers to ensure competency
- Effective incident investigation process
- Inspection and audit process
- Emergency response plan

All of these items are critical to the program regardless of the size and nature of the operations. The complexity of the processes used to identify and manage the risks may vary depending on:

- Size of the facility
- Number of onsite employees
- Level of risk

The size, detail, and complexity of each safety program and its support systems depend on the hazards associated with the plant, the risk associated with each hazard, and the potential impact of the hazard on the people and the surrounding environment.

HEALTH AND SAFETY PROGRAM ELEMENTS

For a successful health and safety program, many elements and steps are incorporated.

Health and Safety Policy

An organization's health and safety policy defines the value that it places on health and safety and sets the benchmark against which all decisions that impact health and safety are judged. It is management's responsibility to establish the health and safety policy for the power plant and their participation in the development and approval of the policy is essential. Only top management can ensure that the necessary financial and human resources needed to implement the policy are made available. They must also model the proper actions and behaviours to demonstrate their commitment to, and ownership of, the safety program itself.

The policy, appropriate for the size and nature of the plant, will include commitment to:

- Establish and maintain a safe and healthful environment
- Comply with regulatory requirements and other appropriate standards
- Provide the necessary resources to develop, support, and maintain the program
- The proactive communication of the policy to all employees
- A process of continuous improvement
- The consequences of non-compliance with safety procedures is also considered in the policy

While good safety behaviour by an individual is best achieved through a process of providing information, encouragement, and coaching, there may come a time when disciplinary action is required. It is important and fair that everyone concerned understands the ultimate consequences of non-compliance.



Initial Status Review

When considering improvements or changes to a power plant's health and safety program, it is important to first conduct a "current status review" of the existing safety program and its functionality. The purpose of a current status review is to determine the state of the plant's existing health and safety program to assist in developing a strategy to move forward to reach the mandate of the goals and objectives of the new program.

Many elements of the overall system may already be in place and can be built upon and incorporated into the new, improved health and safety management system. An initial status review determines the following:

- What elements are already in place
- What needs to be done
- What help and information is available
- What is relevant for the specific plant

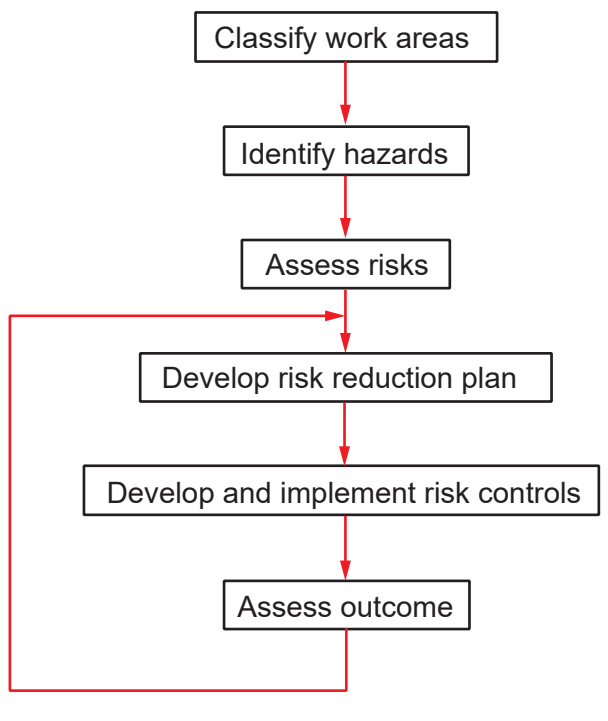
When conducting the initial status review, the current health and safety program is compared against all the elements of the desired system.

An initial status review is not required if a comprehensive program and effective audit system is already in place. The results of past audits indicate where there were shortcomings and where improvement is required.

Risk Reduction Process

One of the main tools used for successfully improving health and safety performance is a **risk based management system**. These programs have three major elements: hazard identification, risk assessment and risk control as shown in Figure 1.

Figure 1 – Risk Reduction Process



Classification of Work Areas

In order to manage the process, it is useful to divide the power plant into a number of work areas (e.g. boiler feed water treatment, boilers, electrical generating equipment, and stack emission control).

Hazard Identification

A hazard is a source or situation with a potential for harm in terms of

- Human injury or ill health
- Damage to property or the environment
- A combination of these

Hazard identification is a systematic process used to identify any condition within the workplace that has the potential to cause injury, property damage or environmental impact. Both routine and non-routine activities such as emergencies and shutdown are also considered.

The process used to identify hazards is dependent on the complexity of the operation and the nature of the risks. Job Analysis, the systematic breaking down of a job into single activities, may be required. For complex plants or where risks are significant, a full HAZOP (Hazard and Operability) study is considered.

During the hazard identification phase, there is no judgement taken regarding either the likelihood or severity of an incident occurring.

Risk Assessment

Risk is the combination of one or more consequences, and the likelihood of a specified hazardous event occurring.

Risk assessment is a systematic process used to assess the risk of all hazards identified during the hazard identification phase. In assessing risk, it is important to use a process that has standard qualifiers that give objective ratings to each hazard to allow for proper response timing. The relative risk of different hazards is sufficient for establishing priorities for risk reduction activities.

Consequences

The consequences or severity of each hazard area are shown in Table 1.

Table 1 – Classes of Hazards	
Hazard Class	Definition
Class A	Minor, non-disabling injury; non-disruptive damage
Class B	Serious, temporary disabling injury or illness; extensive but non-disruptive damage
Class C	Permanent disability, loss of life or body parts, disruptive damage

Likelihood

The likelihood or probability of each hazardous event occurring should be categorized in a manner similar to the following:

- Likely
- Unlikely
- Highly Unlikely



Risk Reduction Plan

A risk matrix similar to Table 2 can then be used to establish priorities for the development of an organized response strategy.

Table 2 – Risk Matrix			
Likelihood/ Consequences	Class A	Class B	Class C
Likely	Moderate Risk	Substantial Risk	Unacceptable Risk
Unlikely	Tolerable Risk	Moderate Risk	Substantial Risk
Highly Unlikely	Trivial Risk	Tolerable Risk	Moderate Risk

The hazards identified using the matrix clearly show where the priorities for action lie.

Risk Controls

Risk controls are developed to reduce hazards to the degree acceptable to the organization by:

- Attempting to eliminate or remove the risk
- Developing appropriate procedures to reduce the consequences or likelihood
- Utilizing personal protective equipment as a last resort

Care must be taken that the introduction of a new risk control to address a specific hazard does not, in itself, create a new hazard.

A risk reduction plan is then developed based on the priorities identified and the availability of resources required to implement the corresponding risk controls. This plan is made available to all employees.

Assessing Outcome

After a period of time, (possibly six months), the effectiveness of new controls for the specified risks is assessed and, if necessary, changes made.

The risk reduction plan, which is developed with input and support from plant personnel, is made available to all. It allows everyone to focus on the higher risks and then do something about them.

Progress measured against this plan is monitored. When milestones are achieved, success in furthering health and safety is demonstrated. When milestones are not achieved, corrective action is taken.

Regulatory Requirements

It is important to know whether all legal requirements, such as acts and regulations, concerning occupational health and safety, boilers and pressure vessels, power engineering and any other applicable regulations, are known and complied with. If not, action to bring the power plant operations into compliance is taken. Procedures to remain current with these requirements are put in place.

Health and Safety Objectives and Plan

To continually improve health and safety performance requires the establishment of annual measurable health and safety objectives.

These objectives support the health and safety policy and address:

- Initial status review findings
- Priorities identified as a result of the risk reduction process
- Any non compliance with regulatory requirements
- Findings from an analysis of past incidents and non-conformances
- Recommendations of the health and safety committee

The objectives are clear, measurable, and articulate the desired outcome. Both the name of the person accountable for achieving the objective and the targeted completion date are stated.

Based on the health and safety objectives, a detailed implementation plan is developed. The plan outlines the actions required and identifies the resources used to achieve each objective. Again, the accountability for each action and the targeted completion date are shown.

Health and safety objectives or goals are included in the yearly performance review strategies for all employees. Their importance needs to be stressed. They are not seen as something separate from or of lesser importance than other goals such as production or costs.

The goals support the achievement of the health and safety objectives, plans and the continuous improvement of health and safety performance. Individual objectives are different for every employee depending on their role and the nature of their job.

They may be project related such as researching alternative boiler feedwater treatment processes that eliminate the use of hazardous chemicals or reviewing and improving the plant's incident investigation procedure. Alternatively, they may be behaviour related such as improvement in the wearing of hearing protection in designated areas.

Roles and Responsibilities

Every person has a responsibility to act at all times in a way that does not jeopardize either their own safety or health nor put their co-workers or others at risk. They are held accountable for complying with all procedures and rules and the requirements of the health and safety program. This includes submitting incident and non-conformance reports such as deviations from required procedures.

However, ultimate responsibility for health and safety rests with management. Top management sets the policy and provides the resources essential for the implementation, control and improvement of the health and safety program.

All those with management responsibilities provide leadership and demonstrate their commitment to the continuous improvement of health and safety performance. They personally demonstrate good safety behaviour and persuasively encourage good safety behaviour on the part of their employees.

They explain the importance of the requirements when transgressions are noted. General accountability for health and safety such as compliance with the plant's health and safety procedures, working in a safe manner, and identifying risks are written into all job descriptions. In addition, specific accountability for defined health and safety activities such as incident investigations and emergency response are also included in job descriptions, where appropriate.



Training, Awareness and Competence

Personnel must be competent to perform tasks that may impact on health and safety in the workplace. To achieve this, competency requirements for individual roles are identified, training needs are analyzed and training programs are identified.

This aspect of the health and safety program is described in more detail under the third learning objective.

CONSULTATION AND COMMUNICATION

Reduction of injuries, plant disruption and property damage are only achieved if all employees are fully engaged. Generally, employees support and follow requirements that they understand, that they believe to be important, that they believe are appropriate, and that they help develop.

Plant management establishes effective consultation and communication processes that encourage participation in good health and safety practices and support for health and safety policies and objectives.

It is important that the front line engineers' knowledge and experience of the day-to-day operations is fully considered when decisions impacting health and safety are taken.

Consultation

Most health and safety legislation suggests that a health and safety committee be established. Depending on the jurisdiction, members of the committee participate in a numbers of functions:

- Assist in creating a safe workplace
- Participate in identifying hazards and making recommendations for controlling these hazards
- Search for new information on health and safety issues in the workplace
- Promote health and safety programs that educate and inform team members
- Review and investigate reports or concerns about health and safety and make recommendations where necessary
- Participate in health and safety inspections and incident investigations
- Make recommendations that establish, enforce, or improve the effectiveness of the occupational health and safety program

While the health and safety committee is the prime conduit for health and safety consultation, it should not be the only one. Opportunities are found to allow other staff to participate in health and safety related projects which builds commitment through involvement and brings other views to the table.

Communication

Formal training programs are designed and implemented to make health and safety practices second nature. One time or infrequent formal training is insufficient: lessons must be reinforced on an ongoing basis. This is accomplished in the following ways:

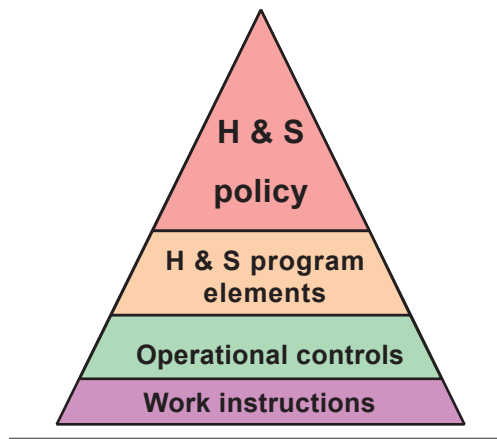
- Work crew health and safety meetings led by the supervisor with support from health and safety committee member, and including a review of a safety topic of the month
- Health and safety updates, bulletins from management or health and safety advisor
- Periodic health and safety briefings from management (preferably verbal), highlighting the state of health and safety in the plant, achievements and shortcomings of the program.

Operational Control (Safety) Procedures

Operational control procedures are written to control risks identified during the risk identification process.

Operational control procedures are applicable to the entire power plant. They should not be confused with detailed operating and maintenance instructions that are only applicable to certain parts of the plant or operations. However, they are complementary to and not separate from the detailed work instructions as can be seen from Figure 2.

Figure 2 – Safety Program



Examples of appropriate operational control procedures for a power plant are:

- Purchasing procedures - ensuring material standards are met
- Hazardous task procedures - safe work practices, including lockout, tagout, confined space entry, and use of personal protective equipment
- Hazardous material handling procedures - including hazardous material storage, handling, and WHMIS
- Maintenance procedures - inspection and testing of protection systems
- Engineering procedures - plant modifications

Document and Data Control

The health and safety program needs to be documented and made available to all employees. Changes to the program are tracked and controlled and no changes are made unless authorized.

Records are kept to demonstrate that the health and safety system operates effectively and that all operations have been carried out under safe conditions. These records include:

- Training records
- Health and safety inspection reports
- Health and safety management system audit reports
- Consultation reports
- Incident reports
- Health and safety committee meeting minutes
- Medical test reports
- Health surveillance reports
- PPE issues and PPE maintenance records
- Reports on Emergency Response drills
- Risk management system audits and progress reports



Emergency Preparedness and Response Plan

Every plant assesses potential major incident and emergency situations and develops an appropriate emergency response plan. Examples of such events include fires and explosions, ruptures, fuel spills, and gas escapes. The plan must include such aspects as:

- Identification of different emergencies
- Alarm systems and emergency equipment
- The make up and duties of the emergency response team
- What action persons not involved in the emergency should take
- Emergency escape routes and assembly points
- Identification of the role of emergency services liaison
- Regulatory and corporate reporting requirements
- Responsibility for media liaison

Practice drills are held periodically to test the plans. The success of the drills is reviewed and any necessary changes made to the plan.

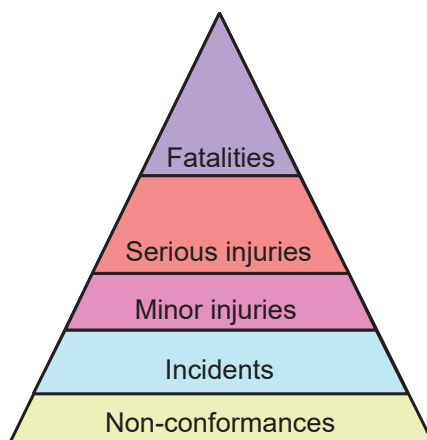
Incident and Non-conformance Reporting and Investigation

Organizations have an effective process for reporting, investigating incidents and non-conformances with safety requirements.

Incidents include both near misses and occurrences of personal injury or equipment damage. Because they can almost always be avoided serious incidents are rarely accidental. For this reason, it is incorrect to refer to these incidents as “accidents.”

The primary purpose of these investigative procedures is to prevent further occurrences of the situation by identifying and dealing with the root causes. In addition, an effective procedure allows legal requirements for reporting of incidents and injuries to be met. Fatalities and serious injuries can be avoided if action is taken to address the underlying causes of non-conformances and incidents. This relationship is shown in Figure 3.

Figure 3 – Degrees of Incident Severity



The process includes procedures for:

- Reporting and investigating incidents and non-conformances
- Identification of actions to be taken to avoid reoccurrence of the risk
- Initiation and completion of corrective and preventive actions
- Confirmation of the effectiveness of corrective and preventive actions taken

A monitoring system is used to ensure that each incident and non-conformance is investigated and the identified corrective action tracked to completion.

Performance Monitoring, Inspection and Auditing

Procedures are put in place to monitor, measure and track health and safety performance, conformance with processes, procedures and instructions, and progress against health and safety goals and objectives.

Measurement indicates:

- What is and is not working
- Where the priorities lie
- Where changes to the health and safety management system and procedures are necessary

Continuous improvement can only be achieved with this information. Effective performance monitoring comprises both reactive and proactive measures.

Examples of reactive measures are:

- Reported unsafe acts and conditions
- Tracking the number of lost time injuries and near misses
- Regulatory agency enforcement action

Examples of proactive measures are:

- Monitoring the progress being made on achieving the overall plant health and safety objectives;
- Observing and recording compliance with procedures (e.g. wearing of protective equipment)
- Auditing the effectiveness of incident and non-compliance investigations and follow-up
- Workplace environmental measurements (e.g. noise and dust)
- Monitoring the frequency and effectiveness of plant safety meetings

Checklists, plant inspections, and health and safety audits are the major tools for proactive monitoring. This aspect of the health and safety program is described in more detail in the next learning objective.



OBJECTIVE 2

Explain the purpose of and the process used for safety checklists, inspections, audits and reviews.

Checklists, inspections, audits and reviews are used to control and measure safety performance in a plant and to establish trends that identify how well the health and safety management system is operating. They are proactive instruments that confirm compliance and provide plant management and employees with information which they can use to prevent incidents.

SAFETY CHECKLISTS

A checklist is a series of standard observations or actions that, when checked off, indicate that the applicable observation or action has been made. A checklist acts as both a memory prompter and a recording document. Power engineers use checklists to record their findings and actions taken while on shift.

The results of the checklists may be used to initiate corrective action, such as the generation of a maintenance work order. Checklists can also be used to track results or provide evidence of the results of the safety procedures.

Examples of common checklists include:

- Emergency equipment tests - emergency alarm, fire pumps, emergency shower
- Housekeeping
- Measuring equipment calibration - explosimeter, oxygen meter
- Shutdown device tests

SAFETY INSPECTIONS

Supervisors use facility safety inspections to determine that the required measures to control hazards are performed on an ongoing basis. Such inspections are conducted on a scheduled basis, usually weekly.

Deficiencies and non-conformances are noted, documented and shared with everyone in the work unit. Action must be taken to correct the deficiencies.

Many supervisors choose to form a team to carry out the inspection. Members of the team include an employee health and safety committee member and a representative from maintenance. Frequently, the supervisor leads the team. This leadership responsibility is not delegated as it underlines the importance that the supervisor places on safety. Furthermore, supervisors are legally responsible to make sure that everything reasonable is done to protect the health and safety of the workers.

At program introduction and periodically thereafter, a more comprehensive inspection is conducted. Table 3 is an example of a comprehensive inspection form for a typical manufacturing facility. A list like this can be used to develop an inspection form specific to a particular plant.

Table 3 – Typical Manufacturing Inspection Checklist

INSPECTORS:		DATE		
		(O) Satisfactory (X) Requires Action		
		Location	Condition	Comments
TRAINING				
Is training provided for each person newly assigned to a job?				
Does initial training include a thorough review of hazards associated with the job?				
Is adequate instruction in the use of personal protective equipment provided?				
Is training for the use of emergency equipment provided?				
Are workers knowledgeable in the "Right to Refuse" procedures?				
ENVIRONMENT				
Are resources available to deal with very hot or very cold conditions (drinking water, lined gloves, insulated boots)?				
Is the rain gear that is provided comfortable, and light enough so as not to constitute a hazard?				
Are work surfaces and grip surfaces safe when wet?				
Do workers know the symptoms of heat cramps, heatstroke?				
WORK PROCESS				
Are repetitive motion tasks properly paced and kept to a minimum?				
Do joint committee members have access to material safety data sheets?				
Are workers informed (by hazard signs and tags)?				
Have all trucks, forklifts and other equipment been inspected and maintained?				
Are lockout procedures followed?				
Is ventilation equipment working effectively?				
Is fume and dust collection hood properly adjusted?				
FIRE EMERGENCY PROCEDURES				
Is there a clear fire response plan posted for each work area?				
Do all workers know the plan?				
Are drills held regularly?				
Are fire extinguishers chosen for the type of fire most likely in that area?				
Are there enough extinguishers present to do the job?				
Are extinguisher locations conspicuously marked?				
Are extinguishers properly mounted and easily accessible?				
Are all extinguishers fully charged and operable?				
Are special purpose extinguishers clearly marked?				



MEANS OF EXIT			
Are there enough exits to allow prompt escape?			
Do employees have easy access to exits?			
Are exits unlocked to allow egress?			
Are exits clearly marked?			
Are exits and exit routes equipped with emergency lighting?			
WAREHOUSE AND SHIPPING			
Are dock platforms, bumpers, stairs and steps in good condition?			
Are light fixtures in good condition?			
Are all work areas clean and free of debris?			
Are stored materials properly stacked and spaced?			
Are tools kept in their proper place?			
Are there metal containers for oily rags and for rubbish?			
Are floors free of oil spillage or leakage?			
Is absorbent available for immediate clean-up of spills and leaks?			
Are all Class I products stored in Class I approved buildings or outside the warehouse?			
LOADING/UNLOADING RACKS			
Are steps, railings and rectangle ramps on raised platforms in good repair?			
Is piping and in-line equipment in good condition and free of leaks?			
Are loading arms operating satisfactorily?			
Do submerged filling two-stage valves operate properly?			
Are bonding and grounding cables free of breaks?			
Are connections tight and sound?			
Is the general condition of wiring and junction boxes, etc. in good condition (visual inspection)?			
LIGHTING			
Is the level of light adequate for safe and comfortable performance work?			
Does lighting produce glare on work surfaced, VDT screen and keyboards?			
Is emergency lighting adequate and regularly tested?			
MACHINE GUARDS			
Are all dangerous machine parts adequately guarded?			
Do machine guards meet standards?			
Are lockout procedures followed when performing maintenance with guards removed?			

ELECTRICAL			
Is the Canadian Electrical Code adhered to in operation, use, repair and maintenance?			
Are all machines properly grounded?			
Are portable hand tools grounded or double insulated?			
Are junction boxes closed?			
Are extension cords out of the aisles where they can be abused by heavy traffic?			
Are extension cords being used as permanent wiring?			
TOOLS AND MACHINERY			
Are manufacturers' manuals kept for all tools and machinery?			
Do power tools conform to standards?			
Are tools properly designed for use by employees?			
Are defective tools tagged and removed from service as part of a regular maintenance program?			
Are tools and machinery used so as to avoid electrical hazards?			
Is proper training given in the safe use of tools and machinery?			
CONFINED SPACES			
Are entry and exit procedures available and adequate?			
Are emergency and rescue procedures in place (e.g. trained safety watchers)?			
HOUSEKEEPING			
Is the work area clean and orderly?			
Are floors free from protruding nails, splinters, holes and loose boards?			
Are aisles and passageways kept clear of obstructions?			
Are permanent aisles and passageways clearly marked?			
Are covers or guardrails in place around open pits, tanks and ditches?			
FLOOR AND WALL OPENINGS			
Are ladder-ways and door openings guarded by a railing?			
Do temporary floor openings have standard railings or someone constantly on guard?			



ELEVATING DEVICES			
Are elevating devices used only within capacity?			
Are capacities posted on equipment?			
Are they regularly inspected, tested and maintained?			
Are controls of the “dead man” type?			
Are operators trained?			
SOUND LEVEL/NOISE			
Are regular noise surveys conducted?			
Is hearing protection available?			
TEMPORARY WORK STRUCTURES			
Are temporary work structures used only when it is not reasonably practicable to use permanent ones?			
Are excavations properly shored, free of large objects (rocks, etc.) at the edges?			
EMPLOYEE FACILITIES			
Are facilities kept clean and sanitary?			
Are facilities in good repair?			
Are cafeteria facilities provided away from toxic chemicals?			
MEDICAL AND FIRST AID			
Is there a hospital or clinic nearby?			
Are there employees trained as first-aid practitioners on each shift worked?			
Are physician-approved first-aid supplies available?			
Are first-aid supplies replenished as they are used?			
PERSONAL PROTECTIVE EQUIPMENT			
Is required equipment provided, maintained and used?			
Does equipment meet requirements?			
Is it reliable?			
Is personal protection utilized only when it is not reasonably practicable to eliminate or control the hazardous substance or process?			
Are warning signs prominently displayed in all hazard areas?			

MATERIALS HANDLING AND STORAGE			
Is there safe clearance for all equipment through aisles and doors?			
Is stored material stable and secure?			
Are storage areas free from tripping hazards?			
Are only trained operators allowed to operate forklifts?			
Is charging of electric batteries performed only in designated areas?			
Are dock boards (bridge plates) used when loading or unloading from dock to truck or dock to rail car?			
Are necessary warning devices and signs in use for railway sidings?			
Are specifications posted for maximum loads which are approved for shelving, floors and roofs?			
Are racks and platforms loaded only within the limits of their capacity?			
Are chain hoists, ropes and slings adequate for the loads and marked accordingly?			
Are slings inspected daily before use?			
Are all new, repaired, or reconditioned alloy steel chain slings proof-tested before use?			
Are pallets and skids the correct type and inspected?			
Do personnel use proper lifting techniques?			
Is the size and condition of containers hazardous to workers?			
Are elevators, hoists, conveyors, balers, etc., properly used with appropriate signals and directional warning signs?			
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SAFETY AUDITS

The purpose of safety audits is to evaluate the effectiveness of each element of the overall health and safety program. Safety audits do not take the place of the regular facility safety inspections whose purpose is to confirm that specific hazards are under control.

Rather than conducting a single annual audit, it is preferable to conduct sub-audits of different elements of the health and safety management process or program throughout the year. Conducting only a single annual safety audit of the whole system may actually hide the facts. The single annual audit approach may tend to create a safety “ramp up” effect, by managers and supervisors, as the audit time approaches. Sub-audits also facilitate continuous improvement as resulting requirements for action to correct deficiencies and improve processes do not all come at one time but are spread throughout the year.

Personnel, not directly responsible for the activity being examined, conduct the audits. These auditors should be familiar with both the company health and safety program and applicable regulatory requirements. They should be impartial and objective and have received training in how to conduct effective audits.



What the Audit Answers

The persons or team designated to conduct the audits takes a fact-finding approach to gathering data. All audit comments, recommendations and corrective actions focus on five questions:

1. Does the program cover all regulatory and best industry practice requirements?
2. Has the program been properly implemented and maintained?
3. Is there documented proof of compliance?
4. Is the program addressing the priority areas of risk?
5. Is the plant's health and safety plan being achieved?

Depending on the subject of the audit, the following areas are examined:

- Employee knowledge
- Written program review
- Program administration
- Record and document review
- Equipment and material
- General area walk-through

Employee Knowledge

Health and safety standards require “effective training.” An effective program ensures that employees have the knowledge required to operate in a safe manner on a daily basis. The level of knowledge required depends on the specific activities, duties and responsibilities in which the employee is involved. Determining an employee's level of knowledge is achieved through written quizzes, formal interviews or informal questions in the workplace.

Written Program Review

During the audit, a comprehensive review of the written program is conducted. This review compares the plant program to requirements for hazard identification and control, required employee training and record keeping as required by the government.

Program Administration

This review checks the implementation and management of specific program requirements. This portion of the audit determines whether the program is being administrated effectively.

Record and Document Review

Records are usually the plant's only means of proving that specific regulatory requirements have been met. The results, recommendations and corrective actions from the previous program audits are reviewed in order to determine whether there has been continuous improvement.

Equipment and Material

This area of an audit reviews the processes that are in place to ensure operability of the equipment and the integrity of materials. In particular, the processes used to confirm the correct operation of hazard control systems must be confirmed to be effective.

General Area Walk-Through

While audits are not designed to be comprehensive physical wall-to-wall facility inspections, a general walk-through of work areas provides additional insight into the effectiveness of safety programs. Auditors take written notes of unsafe conditions and unsafe acts observed during the walk-through. They talk to the people doing the work and ask specific questions.

Planning for the Audit

Planning for an audit involves:

- Establishing and providing the scope of the audit a few days before the audit
- Ensuring that the members of the audit team are knowledgeable and competent to carry out the audit
- Planning the fact gathering (questions, checklists, sample size etc.)
- Ensuring that the results of past audits are available

Review of Findings and Recommendations

After all documents, written programs, procedures, work practices and equipment have been reviewed, the audit team formulates a concise report that details all areas of the program focusing on the five basic questions mentioned in “What The Audit Answers”. Each program requirement is addressed, deficiencies noted, and recommendations for improvement presented.

Publishing Results

It is essential to advise all supervisors and managers of the basic findings and recommendations and to recognize the personnel accomplishments.

Follow-up Action

Appropriate actions to implement each recommendation of the audit is developed. These actions are incorporated into the plant’s health and safety plan together with target dates and accountability. If any recommendation is rejected, the reasons for the rejection need to be properly documented.

ANNUAL SAFETY REVIEW

The Annual Safety Review, sometimes called a Management Review, has a more strategic focus than the monthly audits. The monthly audits focus on whether the system, as designed, is working properly. The Annual Safety Review examines the adequacy, effectiveness and suitability of the program taking into account the organization’s overall business objectives and external as well as internal factors.

Top management conducts the Annual Safety Review and addresses the possible need for changes to policies and objectives in the light of changing circumstances and the commitment to continuous improvement.

Top management reviews the operation of the health and safety management system to assess whether it is being fully implemented and remains suitable for achieving the organization’s stated health and safety policies and objectives.

The Annual Safety review establishes new or updated objectives for continuous improvement appropriate for the upcoming period. Management considers whether or not changes are required to the health and safety management system. Appropriate resources are included in the applicable budget areas.



OBJECTIVE 3

Explain the purpose of and the process used for safety orientation, education, and training.

The successful implementation of an occupational health and safety program is dependent on the effective delivery of information and knowledge through focused and timely training. A health and safety program, however well designed and documented, is only effective if all employees are aware and understand the need for it.

Every plant should have a training program that recognizes the training needs of all persons and all levels in the organization. Supervision and management, who by their leadership and example are fundamental to the success of the program, also require training in safety leadership, communication, coaching and the constructive enforcement of safety programs.

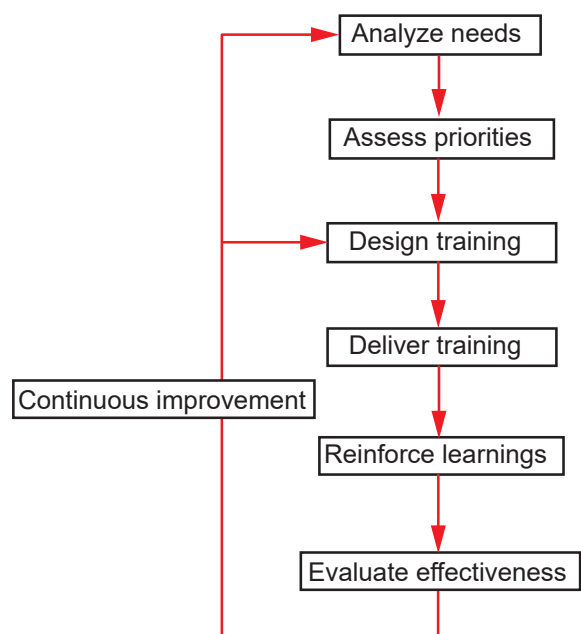
SAFETY ORIENTATION

Contractors, temporary workers and visitors also require training. Procurement contracts for contractors include training requirements. This aspect of contract compliance is audited. The training includes any specific requirements for the plant. Because this can be critical to safe operation, many plants provide safety orientation and training to all contract personnel before they are allowed to work on-site.

EDUCATION

There are many stages associated with implementing an effective training program, as shown in Figure 4.

Figure 4 – H & S Training Programs



Analyze Needs

The first step in the process is a training needs analysis. The competencies required of each position in the organization are established. It must be determined what it is that the person must know and what skills are required to properly and safely perform their duties.

Safety competencies are intrinsically connected to routine plant operation. As a matter of fact, competent plant operation is the single most important safety competency. Safety is unachievable if plant operators are not competent.

Reference is made to the hazards and risks identified as part of the risk reduction process. In many cases, training is identified as a risk control. If necessary, a task analysis, the systematic breakdown of a task into steps, is undertaken in order to establish the skills necessary and the potential hazards of the task. Results of incident investigations and evidence of non-conformances with processes and procedures may also highlight training needs.

In particular, it is important to include any training requirements that are required by legislation or regulation such as WHMIS (Workplace Hazardous Materials Information System).

Assess Priorities

All employees are entitled to know as much as possible about the health and safety hazards to which they are exposed. Employers decide who is in the greatest need of information and instruction and on what aspects. Reference can be made to the plant's Risk Management Program. The highest priority for training is where the highest areas of risk occur and where training has been identified as a risk control.

The employees themselves can also provide valuable information on training priorities. Health and safety training needs can be identified through the employees' responses to such questions as whether anything about their jobs concerns them, if they have had any near-miss incidents or if they feel they are taking risks.

Design Training

Training programs need to have clear objectives and the means of assessing their effectiveness. Training programs are relevant to the plant in question and focused on the plant's specific needs.

An understanding of the current level of competence is essential. This avoids unnecessary training and tailors the training to meet the needs of the employees.

Use can be made of professionally produced videos and other materials that attract the attention of and engage the participant. However, care must be taken to avoid off the shelf solutions that bear little relevance to the operation. In all cases, off the shelf material must be followed up by a discussion that uses specific plant examples to reinforce the learning.

The training design includes mechanisms such as:

- Quizzes and demonstrations to check whether the knowledge has been acquired
- Provision of relevant handout materials
- Ways to reinforce the learning developed

Deliver Training

The following methods are used to deliver training:

- Classroom
- On-the-job
- Computer based



Classroom Training

When classroom training is used, special care must be taken to ensure that the person delivering the training is not only competent but is also an effective training facilitator. This person needs to be able to engage the participants in effective discussion and draw on real world experiences. The ideal person is a plant employee who is knowledgeable in the subject area and an effective trainer.

As indicated earlier, a good understanding of the current knowledge and competence of the potential participants is essential. In cases where it is impossible to avoid a gap in knowledge, the personal experience of the knowledgeable should, wherever possible, be used to reinforce the learning.

On-the-Job Training

On-the-job training is particularly useful where practical skills have to be learned. However, care must be taken to ensure that the person is trained correctly. The correct way of performing the task is documented and the person doing the training receives coaching or instruction in effective on-the-job training methods. A check off system is used to document that the trainee has properly performed the task.

Computer Based Training

Computer Based Training (CBT) is an interactive learning experience between the learner and a computer in which the computer provides the majority of the stimulus. The learner responds and the computer then analyzes the response and provides feedback to the learner. There is a record keeping feature that can save time, maintain accurate training records and diagnose training deficiencies.

CBT Advantages

Computer-based training has the following advantages:

- CBT is the most cost- effective way to train for companies that have facilities on a national or even international scale. Training employees by the conventional means (classroom instruction) requires that the company pay high travel expense costs for the trainer
- CBT is very flexible in that it does not interrupt the trainees' work schedules to train them. CBT optimizes the time available for training, and affords flexibility since training can be taken by most employees on a 24 hour basis without leaving the work site
- CBT is self-paced instructional program that allows for mastery of the material because time is not a constant

CBT Disadvantages

Computer-based training has the following disadvantages:

- CBT does not allow for real-time training
- CBT type of training lacks the face to face contact that classroom instruction allows. Without the face to face with the instructor, the trainee cannot have their questions answered on the spot when they need help

Reinforce Learning

It is also important to recognize that training is not a one time event. Research shows that learning is only achieved when the subject matter is repeated and reinforced over time. Formal training has its place but ongoing reinforcement is essential if the lessons are to be truly learned.

Posters or other reminders that highlight the key learning points are used. Follow-up quizzes that are returned to the trainer are also useful.

One of the best methods is to have the topic included on the agenda of the next shift safety meeting. This allows the topic to be reviewed and discussed in a small, familiar group where people are more likely to voice their opinions and ask questions.

Evaluate Effectiveness

It is important to check that the information provided is not only absorbed and understood at the time of training but also retained over time. Again, this can be done through follow-up quizzes or discussions.

More importantly, it is essential to know whether the training provided has achieved the desired objective. Has the number of incidents due to a particular cause decreased? Has compliance with the targeted procedure improved? Negative results may dictate redesign of the training program or re-evaluation of the appropriateness of training as the risk control.

Continuous Improvement

Like other programs and processes, continuous improvement of the training program over time is required. Training programs may not effectively deliver on their objectives, new hazards may be identified, new methods may be introduced or new technology may become available. In all cases, the training program is updated to ensure that it remains relevant and effective.

TRAINING OF NEW EMPLOYEES

New employees require special consideration. Their health and safety orientation is carefully designed. They know the basic safety rules before starting work within the plant. They understand the:

- Nature of the hazards in the plant
- Significance of the risk
- Importance of personal protective equipment
- Where they may or may not go
- What they can and cannot do

Further learning is provided over time as their operational training progresses. This can be either in the classroom or on-the-job as dictated by the design of the overall plant training program. Proper and safe performance of the task is always demonstrated before the trainee is authorized to perform the task on their own.

Periodic Health and Safety Training

Some worksites experience fairly frequent occupational injuries and illnesses. At such sites, it is especially important that employees receive periodic health and safety training to refresh their memories and to teach new methods of control. New training may also be necessary when regulatory or industry standards require it or industry practices are revised.



One-on-one training is often the most effective training method. The supervisor periodically spends some time watching an individual employee work. Then the supervisor meets with the employee to discuss safe work practices, bestow credit for safe work, and provide additional instruction to counteract any observed unsafe practices. One-on-one training is most effective when applied to all employees under supervision and not just those with whom there appears to be a problem. Positive feedback given for safe work practices is a powerful tool. It helps employees establish safe behavior patterns and recognizes, and thereby reinforces, the desired behavior.

Evaluations

Evaluations help to determine whether the training has achieved its goal of improving the employees' safety performance. Various means of evaluating a training program include:

- Before training begins, observe employees and solicit their opinions to determine what areas need improvement. When training ends, test for improvement. Ask employees to explain their jobs' hazards, protective measures, and test new skills and knowledge
- Keep track of employee attendance at training sessions
- At the end of the training, ask participants to rate the course and the trainer
- Compare pre- and post-training injury and incident rates, near misses and percent safe behaviour exhibited

CHAPTER QUESTIONS

1. Explain the difference between a hazard and a risk.
2. What is the purpose of an Initial Status Review?
3. Why is the involvement of top management in the safety and health program essential?
4. Explain the purpose of operational controls and their relationship to power plant work instructions?
5. Compare the purposes of safety checklists, safety inspections and safety audits.
6. Explain the relationship between the plant's risk reduction plan and its safety training program.
7. Discuss the advantages and disadvantages of computer based training.



CHAPTER 8

Linear Motion

LEARNING OUTCOME

When you complete this chapter you should be able to:

Apply the theory of applied mechanics to bodies at rest and in linear motion.

LEARNING OBJECTIVES

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

1. *Calculate the displacement, velocity, and acceleration of bodies moving in a straight line.*
2. *Calculate the displacements and flight times of projectiles.*
3. *Describe the relationship between mass, force, acceleration and weight.*
4. *Explain inertia, momentum, and conservation of momentum and perform related calculations.*
5. *Demonstrate graphically the relationship between work, force, and distance.*
6. *Define and calculate the kinetic energy of moving objects.*
7. *Define and calculate the potential energy of stationary objects.*
8. *Explain the Law of Conservation of Energy.*
9. *Define and calculate indicated power and power cylinder dimensions.*



OBJECTIVE 1

Calculate the displacement, velocity, and acceleration of bodies moving in a straight line.

INTRODUCTION

Mechanics is the study of the forces acting on objects and their resulting motion. It is widely applicable to problems such as the movement of vehicles and aircraft, the trajectory of a spacecraft, the motion of engine parts, such as a piston, and many other mechanical objects.

Kinematics is the study of motion of objects without taking into consideration forces that act on the object. If forces are considered, the study of motion is called dynamics.

The simplest form of kinematics deals with particles. A **particle** is an object whose size can be ignored when dealing with its motion. A particle may be a small or a large object physically but for the purpose of studying its motion, its orientation and rotation can be ignored. For example, for air traffic control, the aircraft can be considered as a particle because its size is small compared to the distance travelled. When calculating the movement of a vehicle over a long trip, its size and orientation can also be ignored.

Objects move in three dimensions. For some problems, only one dimension is considered and the result is called linear (or sometimes rectilinear) motion. All quantities are scalar (magnitude only) and not vector (magnitude and direction) because only one dimension is involved.

The three quantities required to determine linear motion are displacement, velocity and acceleration.

DISPLACEMENT

The position of an object at any point in time is defined by a coordinate system and therefore is a vector quantity. The difference in position is described as either displacement or distance.

Displacement is a vector quantity that is the difference in position between two points in space.

Distance is a scalar quantity that is the length of a path that a body travels.

When a car travels between two cities, the displacement (or the straight line distance) is usually less than the distance required to travel from one city to another.

In linear motion, distance is actually the relevant measure of position. The term displacement is used in this module so that it is consistent with standard notation.

In SI units, both distance and displacement are measured in metres (m) or a derived measure such as kilometre (km).

SPEED AND VELOCITY

When position is described as a function of time, the movement of a particle is called either speed or velocity.

Speed is a scalar quantity that describes the distance moved in a given time interval.

Velocity is a vector quantity that describes the displacement of an object between two points in time.

In linear motion, speed is the relevant measure of position but the term velocity is used in this module so that it is consistent with standard notation.

In SI units, both speed and velocity are measured in metres/second (m/s) or a derived measure such as kilometre/hour (km/h).

If the distance travelled between two points and the time interval are known, the velocity will be the average velocity and is defined mathematically as:

$$\text{Average Velocity} = \frac{\text{Displacement}}{\text{Time interval}} \text{ or}$$

$$v = \frac{s}{t}$$

If an object increases uniformly from an initial velocity, u , to a final velocity, v , then the average velocity is:

$$v_{\text{ave}} = \frac{u + v}{2}$$

Example 1

A vehicle travels from Calgary to Edmonton, a distance of 300 km, in 3 hours and then continues to Grande Prairie, a distance of 440 km, arriving 5 hours later. What is the velocity for each portion of the trip and the average velocity for the whole trip?

Solution 1

For the Calgary to Edmonton portion:

$$v = \frac{s}{t}$$

$$= \frac{300 \text{ km}}{3 \text{ h}}$$

$$= 100 \text{ km/h (Ans.)}$$

For the Edmonton to Grande Prairie portion:

$$v = \frac{s}{t}$$

$$= \frac{440 \text{ km}}{5 \text{ h}}$$

$$= 88 \text{ km/h (Ans.)}$$

The average speed is:

$$v_{\text{ave}} = \frac{\text{total distance}}{\text{time}}$$

$$= \frac{740 \text{ km}}{8 \text{ h}}$$

$$= 92.5 \text{ km/h (Ans.)}$$



ACCELERATION

Acceleration is a vector quantity that describes the change of velocity with time.

In SI units, acceleration is measured in metres/second² (m/s²).

If the change in velocity is uniform over a time period, then the acceleration or deceleration is constant.

$$\text{Average acceleration} = \frac{\text{Final velocity} - \text{Initial velocity}}{\text{Time interval}} \quad \text{or}$$

$$a = \frac{v - u}{t}$$

For constant acceleration $a = k$, the following relationships between distance, velocity and acceleration can be established.

Final velocity is calculated from initial velocity, acceleration, and time by reorganizing the formula:

$$a = \frac{v - u}{t}$$

$$v = u + at$$

Distance is calculated from the initial velocity, final velocity, and time by substituting formula

$$v = \frac{s}{t} \text{ into the left hand side of formula } v_{\text{ave}} = \frac{u + v}{2}$$

$$v_{\text{ave}} = \frac{u + v}{2}$$

$$\frac{s}{t} = \frac{u + v}{2}$$

$$s = \left(\frac{u + v}{2} \right) \times t$$

Distance can also be calculated from the initial velocity, acceleration, and time by substituting formula $v = u + at$ into formula:

$$s = \left(\frac{u + v}{2} \right) \times t$$

$$s = \left(\frac{u + u + at}{2} \right) t$$

$$= ut + \frac{1}{2} at^2$$

Final velocity is calculated from the initial velocity, acceleration, and distance by reorganizing formula:

$$s = \left(\frac{u + v}{2} \right) \times t$$

$$t = \left(\frac{2s}{u + v} \right)$$

and then substituting this into formula, $v = u + at$:

$$v_f = u + a \left(\frac{2s}{u+v} \right)$$

so that a reorganization of the terms yields:

$$(v - u) = \left(\frac{2as}{u+v} \right)$$

$$(v - u)(u + v) = 2as$$

$$v^2 - u^2 = 2as$$

and the final formula is:

$$v^2 = u^2 + 2as$$

Example 2

A body moving at 20 m/s accelerates uniformly at 4 m/s² for 5 seconds. What is the final velocity and the total distance traveled?

Solution 2

Final velocity is calculated by using the following formula:

$$\begin{aligned} v &= u + at \\ &= 20 \text{ m/s} + (4 \text{ m/s}^2 \times 5\text{s}) \\ &= \mathbf{40 \text{ m/s (Ans.)}} \end{aligned}$$

Distance is then determined:

$$\begin{aligned} s &= \left(\frac{u+v}{2} \right) t \\ &= \left(\frac{20 \text{ m/s} + 40 \text{ m/s}}{2} \right) 5\text{s} \\ &= \mathbf{150 \text{ m (Ans.)}} \end{aligned}$$



Example 3

A vehicle reduces its velocity from 80 km/h to 20 km/h in 10 seconds. What is the deceleration and the total distance traveled?

Solution 3

Since the answer is to be in m/s^2 , convert the velocities from km/h to m/s which is done by the following conversion:

$$\begin{aligned} u &= \frac{80 \text{ km} \times 1000 \text{ m/km}}{1 \text{ h} \times 60 \text{ min/h} \times 60 \text{ s/min}} \\ &= 22.2 \text{ m/s} \end{aligned}$$

$$\begin{aligned} v &= \frac{20 \text{ km} \times 1000 \text{ m/km}}{1 \text{ h} \times 60 \text{ min/h} \times 60 \text{ s/min}} \\ &= 5.56 \text{ m/s} \end{aligned}$$

Deceleration (shown as a negative acceleration) is determined:

$$\begin{aligned} a &= \frac{v - u}{t} \\ &= \frac{5.56 \text{ m/s} - 22.2 \text{ m/s}}{10 \text{ s}} \\ &= -1.66 \text{ m/s}^2 \text{ (Ans.)} \end{aligned}$$

Distance traveled is then calculated:

$$\begin{aligned} s &= ut + \frac{at^2}{2} \\ &= 22.2 \text{ m/s} \times 10 \text{ s} + \frac{-1.66 \text{ m/s}^2 \times (10 \text{ s})^2}{2} \\ &= 139 \text{ m (Ans.)} \end{aligned}$$

OBJECTIVE 2

Calculate the displacements and flight times of projectiles.

“PROJECTILE” DEFINED

For the purposes of this Objective, a **projectile** may be defined as any object that has been projected by a force into the atmosphere at an initial velocity, after which the only force acting upon the object is the force of gravity.

A projectile may be projected horizontally, vertically, or at some angle above the horizontal. In all cases, if we neglect the air resistance, the only force acting upon the projectile is gravity, which acts vertically downwards.

When considering the displacements and flight times of projectiles, we can use the linear motion relationships (as explained in Objective 1) as the basis. That is:

$$s = \left(\frac{u + v}{2} \right) \times t; \quad v = u + a t; \quad a = \frac{v - u}{t}; \quad t = \frac{2s}{u + v}$$

Where:

- s = displacement, in metres (m)
- u = initial velocity, in metres/second (m/s)
- v = final velocity, also in m/s
- a = acceleration, in m/s^2
- t = time, in seconds

VERTICAL PROJECTILE

When a projectile is fired vertically upwards at a known initial velocity, these equations can be directly applied (to determine displacements, velocities, and flight times) because the motion is considered to be linear. Unless some horizontal force is specified, there will be no horizontal motion. Acceleration in this case is -9.81 m/s^2 , which is gravity actually causing the projectile to decelerate vertically. When the projectile reaches its maximum height, its velocity becomes zero and as it falls back to the ground it accelerates at $+9.81 \text{ m/s}^2$.

Three principles to keep in mind with vertical projectiles fired from the ground, assuming no horizontal forces, are: a) final displacement is zero since the object lands exactly where it left the ground; b) flight time ascending equals flight time descending and; c) velocity at landing = velocity when leaving the ground.

HORIZONTAL PROJECTILE

When a projectile is launched horizontally, from a specific height above the ground, other factors must be considered. Initial force and velocity is horizontal, but once in motion the only force acting on the object is the downward force of gravity. This causes the object to take a downward curving flight profile until it hits the ground. This can be explained and demonstrated with the following example.



Example 4: Object projected horizontally

An object is projected horizontally from a height of 100 m above the ground, with an initial velocity of 200 m/s. Neglecting air resistance:

- How long will it take the object to reach the ground?
- What will be the object's displacement from the launch point when it hits the ground?

Solution 4

First, realize that horizontal velocity will remain constant during the flight and the object will accelerate downwards due to the force of gravity acting on it.

- Time taken to reach the ground can be found as follows:

Let the time to reach the ground be 't'.

Then, find vertical velocity, v, when reaching the ground (i.e. immediately before hitting the ground. Yes, true final velocity is zero, but there is no longer flight at that point and the object is no longer a projectile).

$$\begin{aligned} v &= u + a t \\ &= 0 + 9.81 \times t \\ t &= 9.81 t \text{ m/s} \end{aligned}$$

Now find the average vertical velocity.

$$\begin{aligned} \text{Average Velocity} &= \frac{u + v}{2} \\ &= \frac{(0 + 9.81 t) \text{ m/s}}{2} \\ &= 4.905 t \text{ m/s} \end{aligned}$$

From here, use the distance equation to find 't'.

$$\begin{aligned} s &= \left(\frac{u + v}{2} \right) \times t \\ \text{vert. distance} &= \text{ave. vert. velocity} \times \text{vert. time} \end{aligned}$$

$$100 \text{ m} = (4.905 t \text{ m/s}) \times t \text{ s}$$

$$t^2 = \frac{100}{4.905}$$

$$t = \sqrt{20.39}$$

$$= 4.5 \text{ s (Ans.)}$$

- Horizontal and vertical times are obviously the same, so use the time calculated above to determine the horizontal distance.

$$\begin{aligned} \text{horizontal distance} &= \text{horizontal velocity} \times \text{time} \\ &= 200 \text{ m/s} \times 4.5 \text{ s} \\ &= 900 \text{ m} \end{aligned}$$

The question asks for 'displacement', not horizontal distance, so we must use Pythagoras Theorem to find displacement, where displacement is equal to 'c'.

$$\begin{aligned} c^2 &= a^2 + b^2 \\ c &= \sqrt{a^2 + b^2} \\ &= \sqrt{(900 \text{ m})^2 + (100 \text{ m})^2} \\ &= 905.5 \text{ m (Ans.)} \end{aligned}$$

PROJECTILE AT AN ANGLE

When a projectile is fired at an angle to the horizontal, the principles of constant horizontal velocity and of gravity acting on the vertical path are still valid. However, in these scenarios we must factor in the initial angle of projection and use trigonometry to establish vertical and horizontal components of the initial velocity. The following example is used to explain and demonstrate this and carry through to a solution.

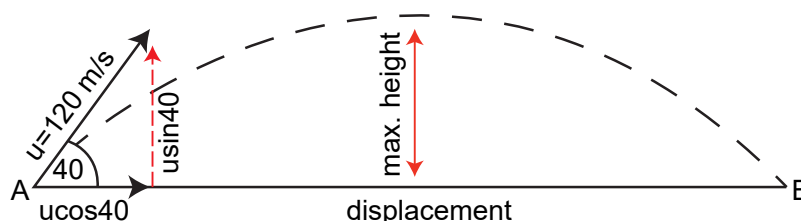
Example 5 - Object projected at an angle.

A projectile is launched from the ground at an angle of 40 degrees above the horizontal. The initial velocity is 120 m/s. Assume there is no air resistance, wind, or other external forces on the object in flight.

- How long will it take the object to return to the ground?
- What maximum height will the object reach during flight?
- How far from its launch point will the object land?

Solution 5

The first thing is to draw a simple diagram to represent the flight. In the diagram, show the angle of launch with the vertical and horizontal vectors of that angle, plus the maximum height and the point of return to the ground. In this case, the diagram should look as follows:



From the diagram, we can see that the vertical component of the initial velocity, u , is $u \sin 40$ and:

$$u \sin 40 = 120 \times 0.6428 = 77.14 \text{ m/s}$$

Likewise, the horizontal component of the initial velocity is $u \cos 40$ and:

$$U \cos 40 = 120 \times 0.766 = 91.92 \text{ m/s}$$



Now, in order to proceed, recognize these three facts: (1) at the maximum height the vertical velocity will be zero; (2) the maximum height occurs at the midpoint (in time and distance) of the flight; and (3) the horizontal velocity remains constant for the entire flight.

- a) In order to find the time to return to the ground, we must find the time to reach maximum height and then multiply by 2.

To find the time to reach maximum height, use linear equation.

$$a = \frac{v - u}{t}$$

$$\text{from which } t = \frac{v - u}{a}$$

In this case, u = initial vertical velocity = 77.14 m/s

v = final vertical velocity = 0 m/s (at max. height)

a = -9.81 m/s^2 (i.e. deceleration due to gravity)

Using these values, the time is:

$$\begin{aligned} t &= \frac{v - u}{a} \\ &= \frac{0 - 77.14 \text{ m/s}}{-9.81 \text{ m/s}^2} \\ &= 7.86 \text{ s} \end{aligned}$$

Therefore, time to return to ground = $2 \times 7.86 \text{ s} = \mathbf{15.72 \text{ s (Ans.)}}$

- b) Now that we know the time to reach maximum height, from above, we can use a linear equation to determine the maximum height.

$$\text{distance} = \text{average velocity} \times \text{time}$$

$$\text{maximum height} = \text{average vertical velocity} \times \text{time}$$

$$\begin{aligned} &= \frac{v + u}{2} \times t \\ &= \frac{77.14 + 0 \text{ m/s}}{2} \times 7.86 \text{ s} \\ &= \mathbf{303.16 \text{ m (Ans.)}} \end{aligned}$$

- c) The distance from launch point to landing point is found using horizontal velocity (which is constant) and the total time.

$$\text{horizontal distance} = \text{horizontal velocity} \times \text{time}$$

$$\begin{aligned} a &= 91.92 \text{ m/s} \times 15.72 \text{ s} \\ &= \mathbf{1444.98 \text{ m (Ans.)}} \end{aligned}$$

OBJECTIVE 3

Describe the relationship between mass, force, acceleration and weight.

MASS

Mass, the amount of matter in an object, is dependent on the volume and density of the substance making up its body. The unit of mass is the kilogram (kg).

FORCE AND ACCELERATION

Newton described the relationship between force, mass, and acceleration in his Second Law. It states that:

“An unbalanced force acting on a body produces an acceleration that is directly proportional to the force and inversely proportional to its mass.”

The formula is therefore:

$$\text{Acceleration} = \frac{\text{Force}}{\text{Mass}}$$

Or

$$\text{Force} = \text{mass} \times \text{acceleration} \text{ or}$$

$$F = m a$$

Force is a derived quantity that is measured in kgm/s² or N (where 1 kgm/s² = 1 N, Newton).

Example 6

A mass of 100 kg is accelerated at 2 m/s². What is the force required to accomplish this?

Solution 6

Accelerating force is determined:

$$\begin{aligned} F &= m a \\ &= 100 \text{ kg} \times 2 \text{ m/s}^2 \\ &= 200 \text{ kgm/s}^2 \\ &= \mathbf{200 \text{ N (Ans.)}} \end{aligned}$$



WEIGHT

Weight is the force of gravity acting on a mass. Objects on the earth are subjected to the force of gravity. Weight varies with location and therefore a person's weight on the moon is different from their weight on earth.

The formula for Newton's Second Law can be rewritten in terms of weight by substituting acceleration due to gravity g for acceleration a so that force becomes weight. The formula then becomes:

$$w = mg$$

$$\text{Where: } g = 9.81 \text{ m/s}^2$$

Weight is measured in N (Newtons) or the same units as force.

Example 7

What is the weight of a 1 kg mass on the earth's surface?

Solution 7

Weight is:

$$\begin{aligned} w &= mg \\ &= 1 \text{ kg} \times 9.81 \text{ m/s}^2 \\ &= 9.81 \text{ kg m/s}^2 \\ &= \mathbf{9.81 \text{ N (Ans.)}} \end{aligned}$$

Example 8

If an object weighs 64 N on the earth's surface, what is its mass?

Solution 8

Mass is:

$$\begin{aligned} m &= \frac{w}{g} \\ &= \frac{64 \text{ kgm/s}^2}{9.81 \text{ m/s}^2} \\ &= \mathbf{6.52 \text{ kg (Ans.)}} \end{aligned}$$

OBJECTIVE 4

Explain inertia, momentum, and conservation of momentum and perform related calculations.

INERTIA

Inertia is a property of matter that causes resistance to a change in motion. Inertia is related to the mass of a body. As mass increases, a greater force is required to change the state of motion of the body or to cause it to accelerate.

Newton's First Law is also called the law of inertia. It states that:

“A body at rest will remain at rest and a body in uniform motion along a straight line will continue unless it is acted upon by an external unbalanced force.”

MOMENTUM

Momentum is the product of the mass of a body and its velocity. Newton's Second Law refers to momentum.

The linear momentum, designated by the letter 'p', may be written as:

$$\text{Momentum} = \text{mass} \times \text{velocity}$$

$$p = mv$$

If the formula for acceleration, $a = \frac{v - u}{t}$, is substituted into formula $F = ma$, then force is stated in terms of a change of momentum.

$$F = ma$$

$$= m \left(\frac{v - u}{t} \right)$$

$$= \frac{mv - mu}{t}$$

$$= \frac{\text{final momentum} - \text{initial momentum}}{\text{time}} = \frac{\text{change in momentum}}{\text{Time}}$$



Example 9

A mass of 2 kg, moving at 10 m/s is brought to rest in 0.005 seconds. What force is required?

Solution 9

v = final velocity, 0 m/s

u = initial velocity, 10 m/s

$$\begin{aligned}
 F &= \frac{mv - mu}{t} \\
 &= \frac{2 \text{ kg} \times 0 \text{ m/s} - 2 \text{ kg} \times 10 \text{ m/s}}{0.005 \text{ s}} \\
 &= \frac{20 \text{ kgm/s}}{0.005 \text{ s}} \\
 &= 4000 \text{ kg m/s}^2 \\
 &= 4000 \text{ N (Ans.)}
 \end{aligned}$$

CONSERVATION OF MOMENTUM

The **Law of Conservation of Momentum** says that when an elastic collision occurs between two objects, and the system is not acted upon by any external forces, the total momentum of the two objects after the collision is equal to the total momentum before the collision. The momentum lost by one object is gained by the other. Also, the change in momentum of one object is equal to the change in momentum of the other.

This can be expressed in equation form. Consider two masses, m_1 and m_2 , with respective velocities of V_1 and v_1 , colliding in a straight line. Their velocities after the collision are V_2 and v_2 , respectively. The equation for conservation of momentum becomes:

total momentum before = total momentum after

$$m_1 V_1 + m_2 v_1 = m_1 V_2 + m_2 v_2$$

from which $m_1 V_1 - m_1 V_2 = m_2 v_2 - m_2 v_1$

and $m_1(V_1 - V_2) = -m_2(v_1 - v_2)$

or $m_1 \times \Delta v = -m_2 \times \Delta v$

change in momentum of ' m_1 ' = change in momentum of ' m_2 '

The negative sign indicates that the changes in momentum, though equal in magnitude, are opposite in direction.

Example 10

A 3 kg object is sitting stationary when it is struck in a linear, elastic collision by another object, travelling at 20 m/s. Striking object loses 5 m/s of velocity, but continues in the same direction. Stationary object is propelled forward, in the same direction, at 18 m/s. Neglecting friction, what is the mass of the striking object?

Solution 10

Since the final velocities are different, we know that the two objects do not remain together and can be treated as separate masses. Also, since the collision is linear, we know that the direction of travel doesn't change and is the same for both objects. This is a relatively simple problem.

Let m_1 be the striking object and V represent its velocity.

Let m_2 be the stationary object and v represent its velocity.

total momentum before = total momentum after

$$m_1 V_1 + m_2 v_1 = m_1 V_2 + m_2 v_2$$

$$\text{and } m_1(V_1 - V_2) = m_2(v_2 - v_1)$$

$$m_1 \times 5 \text{ m/s} = 3 \text{ kg} \times (18 \text{ m/s} - 0 \text{ m/s})$$

$$m_1 \times 5 \text{ m/s} = 54 \text{ kgm/s}$$

$$m_1 = \frac{54 \text{ kgm/s}}{5 \text{ m/s}}$$

$$= 10.8 \text{ kg (Ans.)}$$

Now consider a linear collision in which the two objects become locked together during the collision. After the collision, they will travel together, as a single mass, at a certain velocity.

Example 11

A 25 kg object, travelling at 50 m/s, strikes a second object from behind, travelling in the same direction. The two objects become attached by the collision and continue travelling in the same direction. Struck object has a mass of 15 kg and was travelling at 40 m/s before collision. What is the velocity after the collision?

Solution 11

Since the two objects remain attached, we know that their final velocities will be the same. Since both objects were travelling in the same direction, their initial velocities are both positive.

Let m_1 be the striking object and V_1 represent its initial velocity.

Let m_2 be the stationary object and v_1 represent its initial velocity.

Let V_f be the final velocity.

total momentum before = total momentum after

$$m_1 V_1 + m_2 v_1 = (m_1 + m_2) \times V_f$$

$$25 \text{ kg} \times 50 \text{ m/s} + 15 \text{ kg} \times 40 \text{ m/s} = (25 \text{ kg} + 15 \text{ kg}) \times V_f$$

$$1250 \text{ kgm/s} + 600 \text{ kgm/s} = 40 \text{ kg} \times V_f$$

$$\frac{1850 \text{ kgm/s}}{40 \text{ kg}} = V_f$$

$$V_f = 46.25 \text{ m/s (Ans.)}$$



Example 12

Consider the same two objects in Example 11, but travelling initially in opposite directions. Again, what is the final velocity if the two objects become attached during collision?

Solution 12

In this case, let one object have a positive velocity and the other a negative velocity, to indicate different directions. We'll assume the positive velocity for the 25 kg object. Again, Let V_f be the final velocity.

total momentum before = total momentum after

$$m_1 V_1 + m_2 v_1 = (m_1 + m_2) \times V_f$$

$$25 \text{ kg} \times 50 \text{ m/s} + 15 \text{ kg} \times (-40 \text{ m/s}) = (25 \text{ kg} + 15 \text{ kg}) \times V_f$$

$$1250 \text{ kgm/s} - 600 \text{ kgm/s} = 40 \text{ kg} \times V_f$$

$$\frac{650 \text{ kgm/s}}{40 \text{ kg}} = V_f$$

$$V_f = \mathbf{16.25 \text{ m/s (Ans.)}}$$

Note: The answer is positive, so the direction after collision is the same as the 25 kg object, which we assigned as the positive direction.

OBJECTIVE 5

Demonstrate graphically the relationship between work, force, and distance.

WORK

Work is done when a force moves an object over a certain distance. The formula for work is:

$$\text{Work} = \text{Force} \times \text{Distance} \quad \text{or}$$

$$W = F s$$

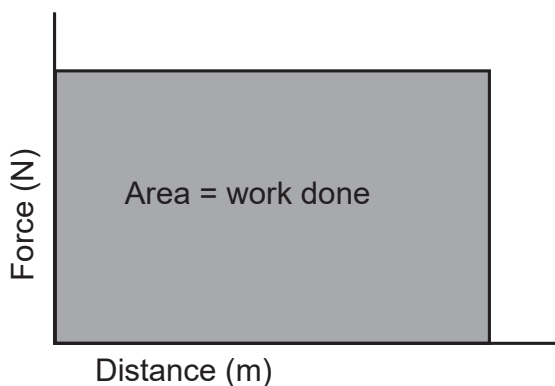
When applied to work, distance is a scalar quantity because the length of the path is proportional to the amount of work done. For example, if a body is moved in a complete circle, work is still done in proportion to the circumference of the circle even though the net displacement is zero. Therefore, work is also a scalar quantity.

It is important to note that distance as it applies to work is in the same direction as the applied force. As an example, if an object is raised using a ramp, the applied force is that of gravity which acts in a vertical direction. The relevant distance is the vertical distance and, assuming a frictionless ramp, the amount of work done is the same regardless of the length or incline of the ramp.

The unit of work is the Joule and one Joule is equal to one Nm (Newton-metre).

It is helpful to display formula $W = Fs$ graphically if the force applied varies with distance. The total work done is determined by the area under the graph. The simplest case occurs when the force is constant for the entire distance, as shown in Figure 1. Formula $W = Fs$ is used to calculate the work done, which is equal to the area under the graph.

Figure 1 – Work Done with a Constant Force

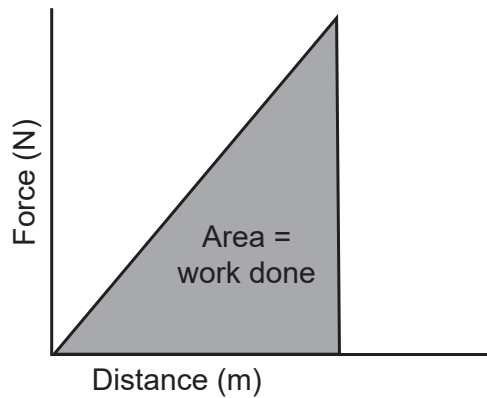


If there is a linear increase in the force, as shown in Figure 2, the area is one half of that in Figure 1 and the formula is:

$$W = \frac{1}{2} F s$$



Figure 2 – Work Done with an Uniformly Increasing Force



Example 13

A mass of 50 kg is moved a distance of 10 m against a force of 100 N. Calculate the amount of work done.

Solution 13

The work is calculated as:

$$\begin{aligned}
 W &= F s \\
 &= 100 \text{ N} \times 10 \text{ m} \\
 &= 1000 \text{ J} \\
 &= \mathbf{1 \text{ kJ (Ans.)}}
 \end{aligned}$$

Note that the mass of the object is irrelevant in this case.

Example 14

A force varying uniformly between 0 and 1000 N moves an object a distance of 20 m. How much work is done?

Solution 14

The work is calculated as:

$$\begin{aligned}
 W &= \frac{1}{2} F s \\
 &= \frac{1}{2} \times 1000 \text{ N} \times 20 \text{ m} \\
 &= 10\,000 \text{ J} \\
 &= \mathbf{10 \text{ kJ (Ans.)}}
 \end{aligned}$$

Example 15

A mass of 50 kg is moved up a frictionless ramp, which is 10 m long and inclined at 45°. How much work is done over the full length of the ramp?

Solution 15

The work required to move the mass up the ramp is the same as the work required to lift it vertically to the height of the ramp. This will be work required to overcome gravity.

First calculate the force required to overcome gravity:

$$\begin{aligned} F &= m a \\ &= 50 \text{ kg} \times 9.81 \text{ m/s}^2 \\ &= 490.5 \text{ kgm/s}^2 \\ &= 490.5 \text{ N} \end{aligned}$$

The vertical distance is determined using basic geometry, in particular using Pythagoras' Theorem, $a^2 + b^2 = c^2$, where 'a' is the vertical height and 'c' is the length of the ramp.

Since the ramp angle is 45° angle, the two sides of the triangle (a and b) are equal and with $c = 10$, the vertical distance, a, may be found as follows:

$$\begin{aligned} a^2 + b^2 &= c^2 \\ 2a^2 &= c^2 \\ a^2 &= \frac{c^2}{2} \\ a^2 &= \frac{(10 \text{ m})^2}{2} \\ a &= \sqrt{\frac{100 \text{ m}^2}{2}} \\ &= \sqrt{50 \text{ m}^2} \\ &= 7.07 \text{ m} \end{aligned}$$

The work done is calculated as:

$$\begin{aligned} W &= F s \\ &= 490.5 \text{ N} \times 7.07 \text{ m} \\ &= 3468 \text{ J} \\ &= 3.47 \text{ kJ (Ans.)} \end{aligned}$$



OBJECTIVE 6

Define and calculate the kinetic energy of moving objects.

WORK AND ENERGY

Energy is the ability to do work. There are different types of energy such as electrical, chemical and heat but the type of energy discussed here is mechanical energy. One type of mechanical energy is kinetic, which is energy due to motion.

KINETIC ENERGY

Kinetic energy is the ability to do work due to the motion of a body.

The kinetic energy E_K of a body at any given time is given by the formula:

$$E_K = \frac{1}{2} m v^2$$

The base unit of measure is the same as that for work, Joules.

When the velocity of a body changes from initial velocity (u) to final velocity (v), the work done is equal to the change in kinetic energy. A formula for this change can be derived from the formula for work, $W = F s$, by substituting ' ma ' for ' F ' (since $F = ma$) as follows:

$$W = F s$$

$$\text{so } W = m a s$$

Since acceleration can be expressed in terms of velocity, from the formula, $a = \frac{v - u}{t}$ the above formula, by substitution, can be written as:

$$W = m a s$$

$$= m s \left(\frac{v - u}{t} \right)$$

The distance, s , can also be replaced in the formula, using $s = \left(\frac{u + v}{2} \right) \times t$:

This substitution plus reorganizing of the equation, gives the work done in terms of the final and initial velocities.

$$\begin{aligned} W &= m s \left(\frac{v - u}{t} \right) \\ &= m \times \left(\frac{v + u}{2} \right) t \times \left(\frac{v - u}{t} \right) \\ &= \frac{1}{2} m v^2 - \frac{1}{2} m u^2 \\ &= \frac{1}{2} m (v^2 - u^2) \end{aligned}$$

Since the work done is equal to the change in kinetic energy, finding one by calculation will also determine the other.

Example 16

What is the kinetic energy of a vehicle of mass 1500 kg travelling at 50 km/h?

Solution 16

The first step is to convert the speed to m/s:

$$\begin{aligned} v &= \frac{50 \text{ km} \times 1000 \text{ m/km}}{1 \text{ h} \times 60 \text{ min/h} \times 60 \text{ sec/min}} \\ &= 13.89 \text{ m/s} \end{aligned}$$

The kinetic energy is then calculated from formula, $E_K = \frac{1}{2} mv^2$ as:

$$\begin{aligned} E_K &= \frac{1}{2} mv^2 \\ &= \frac{1}{2} \times 1500 \text{ kg} \times (13.89 \text{ m/s})^2 \\ &= 750 \times 192.93 \text{ kgm}^2/\text{s}^2 \\ &= 144\,698 \text{ Nm/s} \\ &= 144\,698 \text{ J} \\ &= \mathbf{144.7 \text{ kJ (Ans.)}} \end{aligned}$$



OBJECTIVE 7

Define and calculate the potential energy of stationary objects.

POTENTIAL ENERGY

Another type of mechanical energy is potential energy. Potential energy is the energy available due to the position or state of a body.

Examples of potential energy are:

- The hammer of a pile driver. Maximum potential energy exists at the top position and decreases to zero as the hammer reaches its lowest position.
- Steam in a boiler where the pressure is capable of doing work.
- A piston at top dead centre after the compression stroke where the potential energy is due to pressure. Additional potential energy is supplied when fuel is oxidized to provide additional pressure.
- A spring that has been compressed or extended.
- Water behind a dam which has a potential energy equal to the vertical distance it can drop.

To calculate potential energy, use the same formula $W = Fs$ as that for work. The potential energy is the amount of work that the object is capable of performing due to its current state.

The formula for potential energy is therefore:

$$E_p = F s$$

A standard example is the potential energy due to the elevation of an object. The potential energy of the object is equal to its distance above a reference point, multiplied by the force of gravity.

Example 17

What is the potential energy of an object with a mass of 100 kg that is 10 m above the ground?

Solution 17

It is first necessary to calculate the force of gravity. Using formula $F = ma$:

$$\begin{aligned} F &= ma \\ &= 100 \text{ kg} \times 9.81 \text{ m/s}^2 \\ &= 981 \text{ kgm/s}^2 \\ &= 981 \text{ N} \end{aligned}$$

The potential energy is calculated from formula, $E_p = Fs$ as:

$$\begin{aligned} E_p &= F s \\ &= 981 \text{ N} \times 10 \text{ m} \\ &= 9810 \text{ J} \\ &= \mathbf{9.81 \text{ kJ (Ans.)}} \end{aligned}$$

OBJECTIVE 8

Explain the Law of Conservation of Energy.

LAW OF CONSERVATION OF ENERGY

The Law of Conservation of Energy states that for any process the total energy before and after the process is the same. Another way of saying this is that energy cannot be created or destroyed. It can only be converted from one form to another.

A falling mass is again a good example. Before the object drops from a height, its potential energy is dependent upon its height and the force of gravity. At this point it does not have any kinetic energy. As it falls, the potential energy decreases while the kinetic energy increases by the same amount.

In this situation the formula for the Law of Conservation of Energy can be stated as:

Loss of Potential Energy = Gain in Kinetic Energy

$$Fs = \frac{1}{2}mv^2$$

When the object hits the ground, this kinetic energy is converted into another form. The nature of the remaining energy is dependant on a number of variable factors, including the nature of the material that the object strikes.

Example 18

A 100 kg mass falls from rest at a height of 10 m above the ground. What is its velocity as it reaches the ground?

Solution 18

Since $F = ma$, we can substitute 'ma' for 'F' in the conservation of energy equation, then solve for velocity.

Loss of PE = Gain in KE

$$Fs = \frac{1}{2}mv^2$$

$$m a s = \frac{1}{2}mv^2$$

$$v^2 = \frac{2 m a s}{m}$$

$$v^2 = 2 a s$$

$$v^2 = 2 \times 9.81 \text{ m/s}^2 \times 10 \text{ m}$$

$$v^2 = 196.2 \text{ m}^2/\text{s}^2$$

$$v^2 = \sqrt{196.2 \text{ m}^2/\text{s}^2}$$

$$= 14.01 \text{ m/s (Ans.)}$$



OBJECTIVE 9

Define and calculate indicated power and power cylinder dimensions.

POWER

Power is the rate at which work is done. The formula for power is:

$$\text{Power} = \frac{\text{Work}}{\text{time}} \quad \text{or}$$

$$P = \frac{W}{t}$$

Since the power produced is dependent on time as well as work done, two machines may do the same amount of work over different periods of time and consequently have different power outputs. For this reason, most machines are rated according to their power output and not the amount of work that they can perform.

The unit of measure for power is J/s (Joules/second) which is called a Watt or:

$$1 \text{ J/s} = 1 \text{ Watt}$$

The Watt is a small unit; therefore, power is often measured in larger units, as follows:

$$1 \text{ Kilowatt (kW)} = 10^3 \text{ Watts}$$

$$1 \text{ megawatt (MW)} = 10^6 \text{ Watts}$$

$$1 \text{ gigawatt (GW)} = 10^9 \text{ Watts}$$

Example 19

A constant force of 1000 N moves an object a distance of 1 km in 50 seconds. What is the power required to do this?

Solution 19

The work done is determined from formula $W = Fs$:

$$\begin{aligned} W &= Fs \\ &= 1000 \text{ N} \times 1000 \text{ m} \\ &= 1\,000\,000 \text{ J} \end{aligned}$$

The power is calculated from formula $P = \frac{W}{t}$:

$$\begin{aligned} P &= \frac{W}{t} \\ &= \frac{1\,000\,000 \text{ J}}{50 \text{ s}} \\ &= 20\,000 \text{ Watts} \\ &= \mathbf{20 \text{ kW (Ans.)}} \end{aligned}$$

INDICATED POWER

Indicated power is produced in a reciprocating engine as a result of pressure acting on a piston that moves linearly in a cylinder. The formulas for work and power can be used to determine the amount of power produced by the engine.

The cylinder pressure multiplied by the area of the piston determines the force applied to the piston. The stroke of the piston is the distance through which work is done. The pressure to be used in this calculation is the “mean effective pressure”. It is the net pressure on the piston since there may be an opposing back pressure on the other side of the piston, which must be subtracted from the acting pressure in the cylinder. The mean effective pressure is also an average pressure since the pressure may vary along the stroke as the fluid expands.

Force on the piston is calculated by:

$$\text{Force} = \text{Mean effective pressure} \times \text{area}$$

$$F = p \times A$$

Work done per stroke, where L is the length of the stroke (i.e. the distance), is:

$$\text{Work} = \text{Force} \times \text{distance}$$

$$W = p A L$$

Indicated power, P_i is calculated using the number of power strokes per second, N, so that the final formula is:

$$P_i = p L A N$$

Number of power strokes per revolution is added to the calculation.

For a typical internal combustion engine, the possibilities are:

- A single acting two stroke cycle which provides 1 power stroke per revolution
- A single acting four stroke cycle which provides 1 power stroke per two revolutions.

For a steam engine:

- A double acting two stroke cycle which provides 2 power strokes per revolution.

Note: This calculation can also be used in reciprocating compressor calculations to determine the amount of power required to drive the compressor.



Example 20

A four cylinder two stroke diesel engine runs at 150 rpm and has a mean effective pressure of 1200 kPa. The diameter of each cylinder is 750 mm and the stroke is 1200 mm. What is the indicated power of the engine?

Solution 20

Area of each piston is:

$$\begin{aligned} A &= \pi r^2 \\ &= 3.1416 \times \left(\frac{0.75 \text{ m}}{2} \right)^2 \\ &= 0.442 \text{ m}^2 \end{aligned}$$

With a two stroke engine, there is one power stroke per revolution so the number of strokes per second is:

$$\begin{aligned} N &= \frac{1 \text{ power stroke/rev} \times 150 \text{ rpm}}{60 \text{ sec/min}} \\ &= 2.5 \text{ power strokes per second} \end{aligned}$$

Since 1 kPa is equivalent to 1 kN/m², indicated power produced by each cylinder is calculated using formula, $P_i = pLAN$:

$$\begin{aligned} P_i &= p L A N \\ &= 1200 \text{ kN/m}^2 \times 1.2 \text{ m} \times 0.442 \text{ m}^2 \times 2.5 \text{ strokes/s} \\ &= 1591.2 \text{ kNm/s} \\ &= 1591.2 \text{ kJ/s} \\ &= 1591.2 \text{ kW} \end{aligned}$$

Total power produced by all four cylinders is:

$$\begin{aligned} \text{Total } P_i &= 4 \times 1591.2 \text{ kW} \\ &= \mathbf{6364.8 \text{ kW (Ans.)}} \end{aligned}$$

CHAPTER QUESTIONS

1. A body moving at 10 m/s accelerates uniformly at 5 m/s^2 for 20 seconds. What is the final velocity and the total distance traveled?
2. What force is required to accelerate a 10 kg mass moving at a velocity of 5 m/s^2 ?
3.
 - a) Define momentum.
 - b) Calculate the momentum of a 50 kg mass moving at a velocity of 10 m/s
4. What is the kinetic energy of a vehicle of mass 1000 kg travelling at 36 km/h?
5. A four cylinder 2 stroke diesel engine runs at 210 rpm and has a mean effective pressure of 1000 kPa. The stroke of each cylinder is 1200 mm. The total indicated power for the engine is 6000 kW. Calculate the diameter of each cylinder.
6. A moving 10 kg object strikes a stationary 20 kg object. After linear, elastic collision, the two objects continue, locked together at a velocity of 25 m/s. What was the velocity of the 10 kg object before the collision?
7. A projectile is fired at an upward angle of 30° from the top of a 100 m building. The initial velocity of the projectile is 100 m/s. Ignoring wind and other external factors, find:
 - a) The maximum height, above the ground, reached by the projectile,
 - b) The time for the projectile to reach the ground, and
 - c) The distance from the building that the projectile hits the ground.



CHAPTER 9

Angular Motion

LEARNING OUTCOME

When you complete this chapter you should be able to:

Apply the theory of applied mechanics to bodies in angular motion.

LEARNING OBJECTIVES

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

1. *Define and calculate angular displacement, angular velocity, and angular acceleration.*
2. *Define and calculate moment of inertia, radius of gyration and torque.*
3. *Define and calculate the kinetic energy of rotating masses, including flywheels.*
4. *Define rotational work and power. Calculate brake power and mechanical efficiency of a reciprocating engine.*
5. *Calculate the power transmitted by a belt drive.*
6. *Define centrifugal and centripetal force, centripetal acceleration, and perform calculations involving them.*
7. *Calculate the distance of movement of a governor due to centrifugal force.*
8. *Explain the balancing of masses about a center of rotation and perform simple balancing calculations for single and multiple masses.*



OBJECTIVE 1

Define and calculate angular displacement, angular velocity, and angular acceleration.

INTRODUCTION

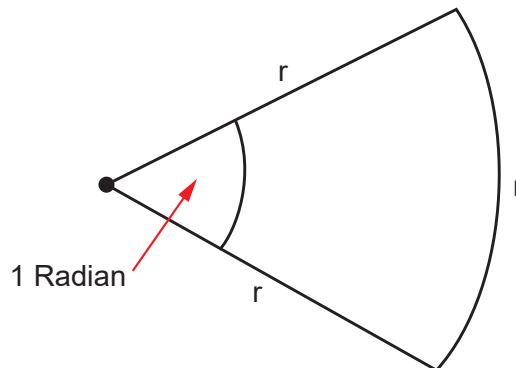
Angular motion, where a rigid body rotates around a fixed axis, is a very important form of motion. All types of rotating equipment have this type of motion, for example, rotors in gas turbines, pumps and compressors and shafts and flywheels in reciprocating engines and compressors.

ANGULAR DISPLACEMENT

The angular displacement of a rotating body is determined by the angle through which it rotates. The angle of rotation is measured by a unit called the radian. As illustrated in Figure 1, a radian is the angle between two radii of a circle when the arc of the sector created by those radii is equal in length to the radius.

The conventional symbol for angular displacement is θ (theta).

Figure 1 – Definition of a Radian



Since the circumference of a circle is $2\pi r$, it follows that there are 2π radians in a complete circle (ie. in one revolution). The general relationship between radians and revolutions can be shown as:

$$1 \text{ revolution} = 2\pi \text{ radians}$$

or

$$1 \text{ radian} = 1/2\pi \text{ revolutions}$$

Since 1 revolution = 360° , one radian = $360/2\pi = 57.2958^\circ$ or 0.159 revolutions.

ANGULAR VELOCITY

Angular velocity is a scalar quantity that describes the angular distance moved in a given time interval. It is normally measured in rad/s (radians/second).

The conventional symbol for angular velocity is ω (omega).

Since engine rotation is usually stated in revolutions per minute, it is often necessary to convert rev/min into rad/s. The conversion is as follows, where: n = the revolutions per minute:

$$\omega \text{ (rad/s)} = \frac{2\pi \text{ (rad/rev)}}{60 \text{ (s/min)}} \times n \text{ (rev/min)}$$

In simplest terms:

$$\omega = \frac{2\pi}{60} \times n \text{ rad/s}$$

If a rotating object increases from an initial angular velocity ω_i to a final angular velocity ω_f , then the average angular velocity will be:

$$\omega_{\text{ave}} = \frac{\omega_i + \omega_f}{2}$$

The angular displacement can be calculated from the average angular velocity by the formula:

$$\text{Angular displacement} = \text{Average angular velocity} \times \text{time}$$

$$\theta = \omega_{\text{ave}} \times t$$

By substitution for ω_{ave} the equation becomes:

$$\theta = \frac{\omega_i + \omega_f}{2} \times t$$

Example 1

What is the angular velocity of a flywheel rotating at 240 rpm?

Solution 1

Using the following formula:

$$\begin{aligned} \omega &= \frac{2\pi}{60} \times n \text{ rad/s} \\ &= \frac{2\pi}{60} \times 240 \text{ rad/s} \\ &= 25.133 \text{ rad/s (Ans.)} \end{aligned}$$



ANGULAR ACCELERATION

Angular acceleration is a scalar quantity that describes the change in angular velocity in a given time interval. It is normally measured in rad/s^2 (radians/second²).

The conventional symbol for angular acceleration is α (alpha).

If the change in angular velocity is uniform over the time period, then the angular acceleration or deceleration is constant.

$$\text{Angular acceleration} = \frac{\text{Final angular velocity} - \text{Initial angular velocity}}{\text{Time interval}}$$

Or

$$\alpha = \frac{\omega_f - \omega_i}{t}$$

Example 2

A flywheel starts rotating from rest and reaches a speed of 200 rpm in 60 seconds. What will be the average angular velocity and angular acceleration?

Solution 2

Convert rpm to rad/s:

$$\begin{aligned}\omega_f (\text{rad/s}) &= \frac{2\pi}{60} \times n \\ &= \frac{2\pi}{60} \times 200 \text{ rad/s} \\ &= 20.94 \text{ rad/s}\end{aligned}$$

Average angular velocity:

$$\begin{aligned}\omega_{\text{ave}} &= \frac{\omega_i + \omega_f}{2} \\ &= \frac{0 \text{ rad/s} + 20.94 \text{ rad/s}}{2} \\ &= \mathbf{10.47 \text{ rad/s (Ans.)}}\end{aligned}$$

The angular acceleration is then determined:

$$\begin{aligned}\alpha &= \frac{\omega_f - \omega_i}{t} \\ &= \frac{20.94 \text{ rad/s} - 0 \text{ rad/s}}{60\text{s}} \\ &= \mathbf{0.349 \text{ rad/s}^2 \text{ (Ans.)}}\end{aligned}$$

Example 3

A pulley wheel of 1 m diameter, rotating at 300 rpm, is brought to rest in 10 seconds. Determine:

- Average angular velocity during rundown
- Angular acceleration
- Number of revolutions made before stopping.

Solution 3

- First, convert rpm to rad/s:

$$\begin{aligned}\omega_i \text{ (rad/s)} &= \frac{2\pi}{60} \times n \\ &= \frac{2\pi \text{ rad/rev}}{60 \text{ s/min}} \times 300 \text{ rev/min} \\ &= 31.42 \text{ rad/s}\end{aligned}$$

Then, find average angular velocity:

$$\begin{aligned}\omega_{\text{ave}} &= \frac{\omega_i + \omega_f}{2} \\ &= \frac{31.42 \text{ rad/s} + 0 \text{ rad/s}}{2} \\ &= \mathbf{15.71 \text{ rad/s (Ans.)}}\end{aligned}$$

- Angular acceleration (actually deceleration in this case)

$$\begin{aligned}\alpha &= \frac{\omega_f + \omega_i}{t} \\ &= \frac{0 \text{ rad/s} - 31.42 \text{ rad/s}}{10\text{s}} \\ &= \mathbf{-3.142 \text{ rad/s}^2 \text{ (Ans.)}}\end{aligned}$$

- The number of revolutions made before stopping.

First, find the angular displacement in radians.

$$\begin{aligned}\theta &= \frac{\omega_i + \omega_f}{2} \times t \\ &= \frac{31.42 \text{ rad/s} + 0 \text{ rad/s}}{2} \times 10\text{s} \\ &= 157.1 \text{ rad}\end{aligned}$$

Then convert radians to revolutions:

$$\begin{aligned}\text{Revolutions} &= \frac{\theta \text{ (radians)}}{2\pi} \\ &= \frac{157.1}{2 \times 3.1416} \\ &= \mathbf{25 \text{ (Ans.)}}\end{aligned}$$

Note that none of the answers is dependent on the diameter of the pulley.



OBJECTIVE 2

Define and calculate moment of inertia, radius of gyration and torque.

MOMENT OF INERTIA

When an object moves in linear motion, its inertia is concentrated in the object's center of mass and moves in the same path as the object. To calculate momentum and work, it is often possible to assume the force is acting at the center of mass and to ignore the distribution of mass in the object.

When an object, such as a flywheel or a shaft, is rotating around its axis, matters are somewhat more complicated since the mass is distributed around the axis at different distances from the center of rotation. This leads to the need to define a moment of inertia that is dependent on the shape of the object and the axis of the rotation. Mass moment of inertia may be defined as “a measure of resistance to rotational acceleration”.

Formulas to calculate the mass moment of inertia have been developed for a variety of common shapes. For example, the mass moment of inertia (designated as 'I'), for a rotating disc (such as a flywheel), with radius 'r' and mass 'm' is:

$$I = \frac{1}{2} m r^2$$

Mass is in kg and flywheel is assumed to be of uniform density. Radius is in meters. Therefore, the units for inertia are kg m².

RADIUS OF GYRATION

Once the moment of inertia has been determined, it is convenient to define an equivalent radius at which the mass can be assumed to be concentrated. This is called the radius of gyration. In formula form, it is defined as:

$$k = \sqrt{\frac{I}{m}}$$

For a flywheel, the radius of gyration can be derived by substituting $\frac{1}{2} m r^2$ for I in the formula:

$$\begin{aligned} k &= \sqrt{\frac{I}{m}} \\ &= \sqrt{\frac{\frac{1}{2} m r^2}{m}} \\ &= \sqrt{\frac{1}{2} r^2} \\ &= 0.707 r \end{aligned}$$

Example 4

A flywheel with a mass of 300 kg and a radius of 1 metre rotates at 300 rpm. What are the moment of inertia and radius of gyration?

Solution 4

Moment of inertia is found:

$$\begin{aligned} I &= \frac{1}{2} m r^2 \\ &= \frac{300 \text{ kg} \times (1 \text{ m})^2}{2} \\ &= 150 \text{ kgm}^2 \text{ (Ans.)} \end{aligned}$$

Radius of gyration:

$$\begin{aligned} k &= 0.707 r \\ &= 0.707 \times 1 \text{ m} \\ &= 0.707 \text{ m (Ans.)} \end{aligned}$$

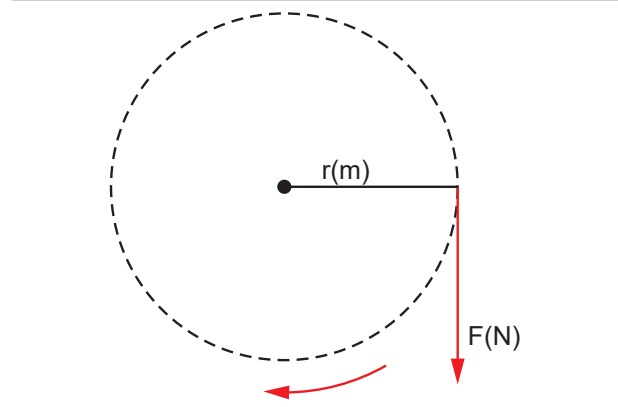
TORQUE

In angular motion, there is a specific way of looking at the force that is applied to a rotating body. This is referred to as torque, which is a measure of how much a force causes a body to rotate (see Figure 2). Torque, T , is defined as the product of force and radial distance, or:

$$T = F \times r$$

The unit is Nm (Newton metres) which is also Joules. However, for torque, Nm is always used, rather than Joule (to avoid confusion with Joules of energy). Energy is a scalar quantity while torque is a vector.

Figure 2 – Torque Diagram



It is important to note that the force used in the torque formula is tangential or perpendicular to the radius. If the force acts in a different direction, the tangential component must be determined to calculate torque. Also, if the direction of the force acts through the center of rotation of the body, then the torque will be zero.



Example 5

A force of 70 N is applied tangentially to a wheel with a diameter of 1 m. What is the torque?

Solution 5

Torque is calculated as:

$$\begin{aligned} T &= F \times r \\ &= 70\text{N} \times 0.5\text{m} \\ &= 35 \text{ Nm (Ans.)} \end{aligned}$$

TORQUE AND ANGULAR ACCELERATION

If a body is rotating and a force is applied with no counteracting force, the body will accelerate (or decelerate if the force is applied in the opposite direction of rotation). The acceleration or deceleration is described by Newton's Second Law and the formula, $F = ma$. Since the linear and angular acceleration are related by the formula:

$$a \text{ (m/s}^2\text{)} = \alpha \text{ (rad/s}^2\text{)} \times r \text{ (m)}$$

then, by substitution, force may be shown by the formula:

$$F = m \alpha r$$

If both sides of the equation are multiplied by "r", it becomes:

$$F r = m \alpha r^2$$

But $F \times r$ is the torque, T , causing the acceleration, so the formula can be written as:

$$T = m \alpha r^2$$

Since the mass is rarely concentrated only at the rim, it may be necessary to use the radius of gyration k which then results in the formula:

$$T = m \alpha k^2$$

By substitution, the torque causing the acceleration can be expressed in terms of the moment of inertia and the angular acceleration:

$$T = m \alpha k^2$$

but

$$I = m k^2$$

therefore

$$T = I \alpha$$

Comparing the linear and angular versions of Newton's Second Law, torque is analogous to force, moment of inertia is analogous to mass and linear acceleration is analogous to angular acceleration.

Example 6

A flywheel with a mass of 200 kg is brought from standstill to 600 rpm in 40 seconds. If the radius of gyration is 500 mm, what torque is required?

Solution 6

First, convert rpm to rad/s:

$$\begin{aligned}\omega_f (\text{rad/s}) &= \frac{2\pi}{60} \times n \\ &= \frac{2\pi \text{ rad/rev}}{60 \text{ s/min}} \times 600 \text{ rev/min} \\ &= 62.83 \text{ rad/s}\end{aligned}$$

Then, determine the angular acceleration:

$$\begin{aligned}\alpha &= \frac{\omega_f - \omega_i}{t} \\ &= \frac{62.83 \text{ rad/s} - 0 \text{ rad/s}}{40\text{s}} \\ &= 1.571 \text{ rad/s}^2\end{aligned}$$

Torque is then derived:

$$\begin{aligned}T &= m \alpha k^2 \\ &= 200 \text{ kg} \times 1.571 \text{ rad/s}^2 \times (0.5\text{m})^2 \\ &= 78.55 \text{ Nm (Ans.)}\end{aligned}$$



OBJECTIVE 3

Define and calculate the kinetic energy of rotating masses, including flywheels.

KINETIC ENERGY

Kinetic energy is the ability to do work due to the motion of a body.

Kinetic energy E_k can be calculated by the following formula which was derived in the module on linear motion (PE2-1-8).

$$E_k = \frac{1}{2} mv^2$$

It is customary to express the velocity in terms of angular velocity as expressed by the formula

$$v = \omega r$$

Radius used is the radius of gyration $r = k$ as described in the previous objective.

Formula for kinetic energy then becomes:

$$\begin{aligned} E_k &= \frac{1}{2} mv^2 \\ &= \frac{1}{2} m \omega^2 k^2 \end{aligned}$$

Units for kinetic energy are the same as those for work, Joules.

Example 7

A flywheel with a mass of 500 kg and a radius of gyration of 0.5 metres rotates at 150 rpm. What is the kinetic energy?

Solution 7

Convert rpm to rad/s:

$$\begin{aligned} \omega \text{ (rad/s)} &= \frac{2\pi}{60} \times n \\ &= \frac{2\pi \text{ rad/rev}}{60 \text{ s/min}} \times 150 \text{ rev/min} \\ &= 15.71 \text{ rad/s} \end{aligned}$$

Kinetic energy is then calculated:

$$\begin{aligned} E_k &= \frac{1}{2} m \omega^2 k^2 \\ &= 0.5 \times 500 \text{ kg} \times (15.71 \text{ rad/s})^2 \times (0.5 \text{ m})^2 \\ &= 15\,425 \text{ J} \\ &= \mathbf{15.43 \text{ kJ (Ans.)}} \end{aligned}$$

OBJECTIVE 4

Define rotational work and power. Calculate brake power and mechanical efficiency of a reciprocating engine.

ROTATIONAL WORK

The work performed by a rotating body is derived from the basic formula for work; i.e. force $\times$ distance. In this case, the distance is the circular distance traveled by the applied force. For angular motion, in one revolution:

$$W = F \times 2\pi r$$

$$\text{but } F \times r = T \text{ (torque)}$$

$$\text{so } W = 2\pi T \text{ Nm}$$

This work can be expressed in terms of the angular displacement, θ , as follows:

We know that in one revolution, the angular displacement, $\theta = 2\pi$ radians. This allows us to substitute ' θ ' for the ' 2π ' in the above equation, creating the general equation at:

$$W = T \theta \text{ Nm}$$

ROTATIONAL POWER

$$\text{Power} = \frac{\text{Work}}{\text{time}}$$

$$\text{in 1 revolution, } \text{Power} = \frac{2\pi T}{\text{time}} \quad (\text{since Work} = 2\pi T)$$

$$\text{at 1 rpm, } \text{Power} = \frac{2\pi T \text{ Nm}}{60 \text{ s}} \quad (\text{since time} = 60\text{s})$$

$$\text{therefore, at } n \text{ rpm, } \text{Power} = \frac{2\pi T n}{60} \text{ Nm/s}$$

$$\text{but: Angular Velocity, } \omega = \frac{2\pi n}{60}$$

$$\text{therefore: } \text{Power} = T \omega \text{ Nm/s}$$

Note: This equation can also be derived from angular displacement, θ :

$$\text{Power} = \frac{\text{Work}}{\text{time}} = \frac{T\theta}{t}$$

$$\text{but: Angular velocity, } \omega = \frac{\theta}{t}$$

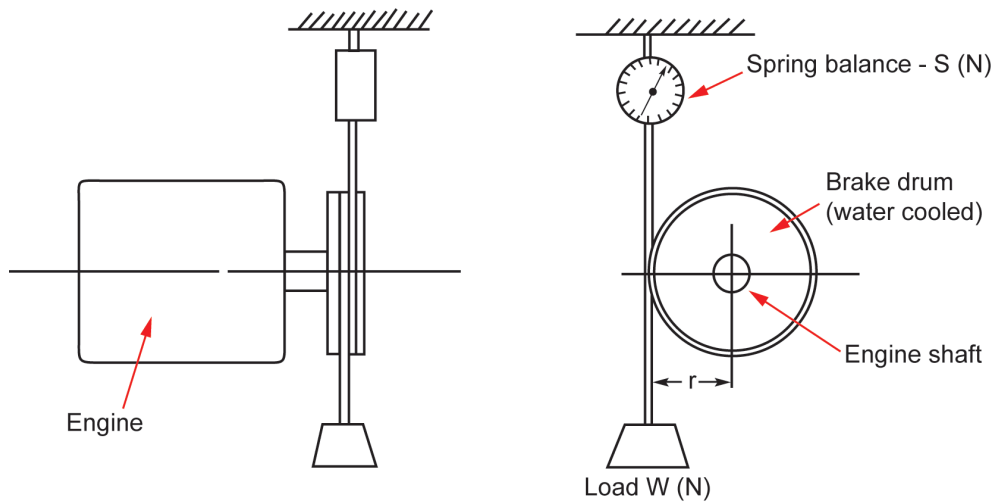
$$\text{therefore: } \text{Power} = T \omega \text{ Nm/s}$$



BRAKE POWER

The power of an engine is usually measured at the output shaft. It is normally referred to as “brake power” because a device called a rope brake is often used to measure the power. A rope brake arrangement is shown in Figure 3.

Figure 3 – Rope Brake



As Figure 3 shows, the rope is turned once around a brake drum. One end of the rope is attached to a spring balance and the other end is attached to a weight. The difference between the downward force ($F = mg$) due to the weight and the upward force (S) measured by the spring balance becomes the net force applied to the drum (i.e. $F = mg - S$). Given the radius and rpm of the flywheel, the torque and angular velocity can be determined and used to calculate brake power.

$$\begin{aligned}
 P_{\text{brake}} &= T \omega \quad \text{where: } T = F \times r \text{ and } \omega = \frac{2\pi n}{60} \\
 &= F \times r \times \frac{2\pi n}{60} \\
 &= (mg - S) \times r \times \frac{2\pi n}{60} \\
 &= (mg - S) \times \frac{2\pi r n}{60}
 \end{aligned}$$

Example 8

A brake power test was carried out using a brake with a radius of 600 mm and a weight with a mass of 25 kg. Engine was rotating at 360 rpm and reading on the spring balance was 50 N. What is the brake power produced, in kW?

Solution 8

$$\begin{aligned}
 P_{\text{brake}} &= (mg - S) \times \frac{2\pi r n}{60} \\
 &= (25 \text{ kg} \times 9.81 \text{ N/kg} - 50 \text{ N}) \times \frac{2\pi \times 0.6 \text{ m/rev} \times 360 \text{ rev/min}}{60 \text{ s/min}} \\
 &= 4416.5 \text{ Nm/s} \\
 &= 4416.5 \text{ W} \\
 &= \mathbf{4.42 \text{ kW (Ans.)}}
 \end{aligned}$$

MECHANICAL EFFICIENCY

Due to friction and mechanical losses, the power available at the output shaft is less than that actual (indicated) power developed inside the engine. The ratio of the brake power to the indicated power is called the mechanical efficiency, which is expressed as a percentage, usually in the range of 90-95%.

$$\begin{aligned}
 \text{Mechanical efficiency (\%)} &= \frac{\text{Brake power}}{\text{Indicated power}} \times 100 \text{ or} \\
 \eta_m &= \frac{P_b}{P_i} \times 100
 \end{aligned}$$

Example 9

The indicated power for an engine is calculated as 7500 kW. Brake power is measured as 7000 kW. What is the mechanical efficiency of the engine?

Solution 9

Mechanical efficiency is:

$$\begin{aligned}
 \eta_m &= \frac{P_b}{P_i} \times 100 \\
 &= \frac{7000 \text{ kW}}{7500 \text{ kW}} \times 100 \\
 &= \mathbf{93.3\% \text{ (Ans.)}}
 \end{aligned}$$



OBJECTIVE 5

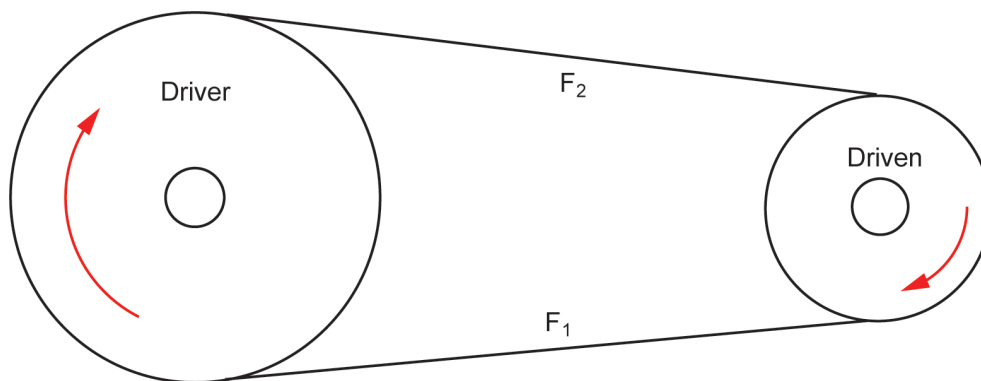
Calculate the power transmitted by a belt drive.

TRANSMISSION OF POWER BY BELT DRIVES

Rotational power may be transmitted from one machine (the driver) to another (the driven) through pulleys, which are connected by a continuous belt. If the belt is tight and there is sufficient surface area between the belt and the pulleys, the friction will be sufficient that the belt will not slip and the rotational power developed by the driver will be transferred to the driven machine.

Figure 4 shows a belt drive arrangement. One side of the belt will be tighter (under greater tension) than the other, depending on which direction the driver is turning. In Figure 4, force F_1 (the tension in the tight side) is pulling on the driven pulley while F_2 (the tension in the slack side) is opposing the turning. This results in an effective driving force of $F_1 - F_2$ Newtons.

Figure 4 – Belt Drive



The power transmitted to the driven pulley can be calculated from the rotational formula:

$$\begin{aligned}
 P &= T \omega \quad (\text{where: } T = F \times r \text{ and } \omega = \frac{2\pi n}{60}) \\
 &= F \times r \times \frac{2\pi n}{60} \\
 &= (F_1 - F_2) \times r \times \frac{2\pi n}{60} \\
 &= (F_1 - F_2) \times \frac{2\pi r n}{60}
 \end{aligned}$$

Example 10

A pulley of 300 mm diameter is driven at 200 rpm by a belt. The tension on the tight side is 2000 N and the tension on the slack side is 500 N. If we neglect the thickness of the belt, what is the power transmitted, in kW?

Solution 10

Given:

$$\text{pulley radius} = 150 \text{ mm} = 0.15 \text{ m}$$

$$\text{pulley speed} = 200 \text{ rpm}$$

$$\text{tight side tension} = 2000 \text{ N}$$

$$\text{slack side tension} = 500 \text{ N}$$

$$\begin{aligned} P &= (F_1 - F_2) \times \frac{2\pi r n}{60} \\ &= (2000 - 500) \text{ N} \times \frac{2\pi \times 0.15 \text{ m/rev} \times 200 \text{ rev/min}}{60 \text{ min/s}} \\ &= 4712 \text{ Nm/s} \\ &= 4712 \text{ W} \\ &= \mathbf{4.712 \text{ kW (Ans.)}} \end{aligned}$$

Note: The example said to ignore the belt thickness. However, if the belt thickness is taken into account, the radius at which the force acts must be increased by one half of the belt thickness. For example, if we consider a belt thickness of 15 mm in Example 10, the new radius will be 157.5 mm (0.1575m) and the power transmitted will increase slightly.

$$\begin{aligned} P &= (F_1 - F_2) \times \frac{2\pi r n}{60} \\ &= (2000 \text{ N} - 500 \text{ N}) \times \frac{2\pi \times 0.1575 \text{ m/rev} \times 200 \text{ rev/min}}{60 \text{ min/s}} \\ &= 4948 \text{ Nm/s} \\ &= 4948 \text{ W} \\ &= \mathbf{4.948 \text{ kW}} \end{aligned}$$



OBJECTIVE 6

Define centrifugal and centripetal force, centripetal acceleration, and perform calculations involving them.

CENTRIFUGAL AND CENTRIPETAL FORCES

Newton's first law of motion states that an object in motion tends to stay in motion, with the same speed and in the same direction, unless acted upon by an unbalanced force. For example, a stone is fastened to the end of a string and whirled around in a circular path. Inward forces must be constantly exerted to keep it travelling in the circle even though the stone itself is exerting an outward radial pull.

Centrifugal Force

Centrifugal force is the outward radial force created by the stone, travelling in a circular path, having the tendency to fly off and travel in a straight line.

Centripetal Force

Centripetal force is the inward pull that is required to counteract the outward radial force and keep the stone on its circular path. The centripetal force must be equal in magnitude to the centrifugal force but act in an opposite direction (Newton's third law of motion).

Centripetal and centrifugal forces can be calculated from Newton's Second Law.

$$\text{Force} = \text{mass} \times \text{acceleration}$$

or

$$F_c = \frac{mv^2}{r} \text{ or } F_c = m \omega^2 r$$

Units of measure are:

m = mass, kg

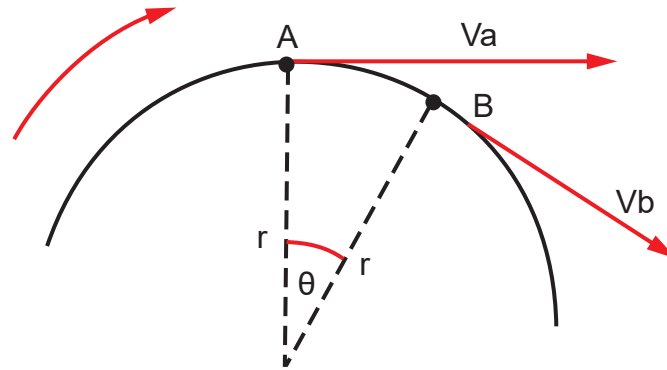
v = velocity, m/s

r = radius, m

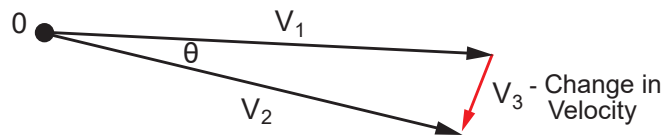
ω = angular velocity, rad/s

F = force, N

Referring to Figure 5, a body moves at a constant speed around a circle with radius = r . At the instant the body passes point A, its velocity is v_a in the direction tangential to the circle at A. As the body passes point B, its velocity is now v_b tangential to the circle at B. Even though the body maintains a constant speed, its velocity has changed due to there being a change in direction.

Figure 5 – Rotating Velocity Vectors


Consider the movement from point A to B be through angle θ . To calculate the change in velocity, the velocity vector diagram is drawn, as shown in Figure 6.

Figure 6 – Velocity Vectors Diagram


Since θ is considered a small angle, the triangle base angles are almost 90° , so we can treat the triangle as a 90° triangle. For small angles, it is true that the values of $\sin\theta$, $\tan\theta$ and θ radians are almost equal; using this “equality” we can show how the change in velocity is related to the original velocity.

$$\sin \theta = \frac{V_3}{V_1} \quad \text{and} \quad \tan \theta = \frac{V_3}{V_2}$$

$$\text{so } V_3 = V_1 \sin \theta \quad \text{so } V_3 = V_2 \tan \theta$$

$$\text{but } V_1 = V_2$$

$$\begin{aligned} \text{so } V_3 &= V_1 \sin \theta \\ &= V_1 \tan \theta \\ &= V_1 \theta \text{ rad} \end{aligned}$$



CENTRIPETAL ACCELERATION

Since the body is travelling at constant speed, its acceleration is due to the constantly changing velocity (due to changing direction) as the body travels in its circular path. This acceleration, directed toward the center of the circle, is referred to as **centripetal acceleration**.

The time for the body to travel from one velocity vector to the next one (a distance of $r\theta$) is determined by:

$$\begin{aligned}\text{time} &= \frac{\text{distance}}{\text{speed}} \\ &= \frac{r\theta}{v}\end{aligned}$$

A change in velocity is equal to $v\theta$ rad and, with a change in velocity, there is acceleration. Acceleration can be determined by:

$$\begin{aligned}\text{Acceleration} &= \frac{\text{change in velocity}}{\text{time}} \\ &= \frac{\frac{v\theta}{r\theta}}{\frac{r\theta}{v}} \\ &= \frac{v\theta \times v}{r\theta} \\ &= \frac{v^2}{r}\end{aligned}$$

Since the motion is circular, the velocity of the body can be expressed in angular measurement, ω rad/s, rather than the linear, v . Using the known relationship, $v = \omega r$, we can substitute in the above equation to determine centripetal acceleration, as follows:

$$\begin{aligned}\text{Centripetal acceleration, } a_c &= \frac{v^2}{r} \\ &= \frac{\omega^2 r^2}{r} \\ &= \omega^2 r\end{aligned}$$

The units of measure for centripetal acceleration are m/s^2 , which should not be confused with the units for angular acceleration which are rad/s^2 .

**Example 11**

A mass of 5 kg rotates at 200 rpm in a radius of 500 mm. What are the centripetal acceleration and force?

Solution 11

First, convert rpm to rad/s:

$$\begin{aligned}\omega \text{ (rad/s)} &= \frac{2\pi}{60} \times n \\ &= \frac{2\pi}{60} \times 200 \\ &= 20.94 \text{ rad/s}\end{aligned}$$

Then the centripetal acceleration is found by:

$$\begin{aligned}a_c &= \omega^2 r \\ &= (20.94)^2 \times 0.5 \\ &= \mathbf{219.24 \text{ m/s}^2 \text{ (Ans.)}}\end{aligned}$$

Now, the centripetal force is obtained:

$$\begin{aligned}F &= m \omega^2 r \\ &= 5 \times (20.94)^2 \times 0.5 \\ &= \mathbf{1096.2 \text{ N (Ans.)}}\end{aligned}$$



CENTRIFUGAL FORCES IN ROTATING EQUIPMENT

Centrifugal forces create substantial forces in the rotating components of machinery. For this reason, there are always speed limitations placed on rotating machinery, often with overspeed protection, to prevent mechanical failure.

Example 12

An axial compressor rotates at 6000 rpm. In one of the compressor stages, the mass of a blade is 0.1 kg and the center of mass is 0.75 m from the center of rotation. What is the centrifugal force on the blade?

Solution 12

First convert rpm to rad/s:

$$\begin{aligned}\omega \text{ (rad/s)} &= \frac{2\pi}{60} \times n \\ &= \frac{2\pi}{60} \times 6000 \\ &= 628.32 \text{ rad/s}\end{aligned}$$

The centrifugal force is then:

$$\begin{aligned}F_c &= m \omega^2 r \\ &= 0.1 \times (628.32)^2 \times 0.75 \\ &= 29\,609 \text{ N} \\ &= \mathbf{29.61 \text{ kN (Ans.)}}\end{aligned}$$

OBJECTIVE 7

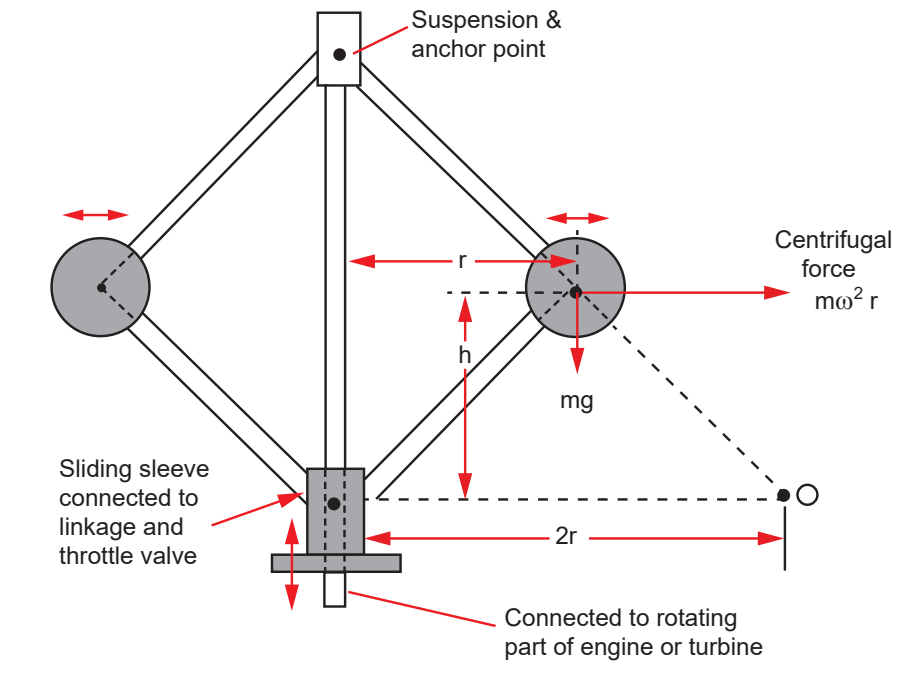
Calculate the distance of movement of a governor due to centrifugal force.

GOVERNORS

A governor is a device used to control the speed of an engine. It was introduced by Isaac Watt to control the steam engine and several versions have become common on different types of engines. Mechanical governors are now being replaced by electronic versions.

Figure 7 illustrates the principles associated with a Watt governor. The sliding sleeve is connected to a mechanism which is attached to a throttle valve that controls steam or fuel flow. When the speed is zero, the sliding sleeve drops and the fly-balls are at their innermost position. The throttle is fully open at this point. As the speed increases, the fly-balls move outward due to centrifugal force and the throttle valve moves toward closed position, until a point of equilibrium is reached. If an increase in load causes a drop in speed, the governor will cause the throttle to open until the original speed is re-established.

Figure 7 – Mechanical Governor



To know the position of the throttle at a certain speed, it is necessary to calculate the height of the weights, also known as the height of the governor, which is shown as h in Figure 7. Height can be calculated by considering the moments around the point O. Clockwise moment consists of the centrifugal force multiplied by the height, or:

$$\text{clockwise moment} = m \omega^2 r h$$



The anticlockwise moment is determined by the force of gravity acting on the mass of the fly-ball; therefore:

$$\text{anticlockwise moment} = m g r$$

Since the clockwise and anticlockwise moments will be in equilibrium (i.e they will be equal) at the governed speed, the final formula for the height can be created by equating the moments and solving for 'h':

$$\text{clockwise moments} = \text{anticlockwise moments}$$

$$m \omega^2 r h = m g r$$

$$\text{from which} \quad h = \frac{g}{\omega^2}$$

It is interesting to note that height is not dependent on the mass of the fly-ball, but only on the force of gravity and the rotational speed.

Example 13

A Watt governor rotates at 100 rpm. What is the height of the governor weights?

Solution 13

Convert rpm to rad/s:

$$\begin{aligned} \omega \text{ (rad/s)} &= \frac{2\pi}{60} \times n \\ &= \frac{2\pi}{60} \times 100 \\ &= 10.47 \text{ rad/s} \end{aligned}$$

Now, the height will be:

$$\begin{aligned} h &= \frac{g}{\omega^2} \\ &= \frac{9.81}{(10.47)^2} \\ &= 0.0895 \text{ m} \\ &= \mathbf{89.5 \text{ mm (Ans.)}} \end{aligned}$$

OBJECTIVE 8

Explain the balancing of masses about a center of rotation and perform simple balancing calculations for single and multiple masses.

BALANCING A SINGLE MASS

If the centrifugal forces within a rotating component, such as a turbine rotor, are not balanced, excessive vibration and possible damage may result. If the position of the mass causing imbalance is known, it is possible to counteract the centrifugal force by providing an equal mass at a diametrically opposite position at the same distance from the center of rotation. This symmetry is not often practical, but it is possible to determine the position and/or the size of a balancing mass that will create the centrifugal force necessary to counteract the imbalance.

For two masses, m_1 and m_2 , which are diametrically opposed to each other (i.e. both on the same diameter) and at distances, r_1 and r_2 respectively, from the center of rotation, the underlying principle in balancing is that the centrifugal force created by one is equal to the centrifugal force created by the other. In equation form this is:

$$m_1 \omega^2 r_1 = m_2 \omega^2 r_2$$

However, since both masses have the same angular velocity, these velocities cancel each other and the mass/radius relationship becomes:

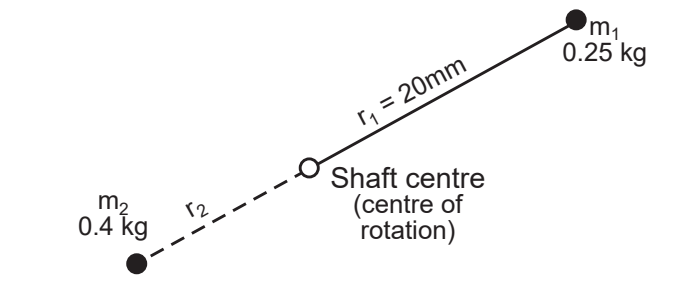
$$m_1 r_1 = m_2 r_2$$

Example 14

A shaft has an unbalanced mass of 0.25 kg at a radius of 20 mm from the center of rotation. At what radius and position should a mass of 0.4 kg be placed for balance?

Solution 14

Figure 8 – Balancing Diagram for Single Mass



$$\begin{aligned} m_1 r_1 &= m_2 r_2 \\ 0.25 \text{ kg} \times 20 \text{ mm} &= 0.4 \text{ kg} \times r_2 \\ r_2 &= \frac{0.25 \text{ kg} \times 20 \text{ mm}}{0.4 \text{ kg}} \\ &= 12.5 \text{ mm (Ans.)} \end{aligned}$$

The position is as shown in Figure 8, diametrically opposite of the 0.25 kg mass and 12.5 mm from the center of rotation.



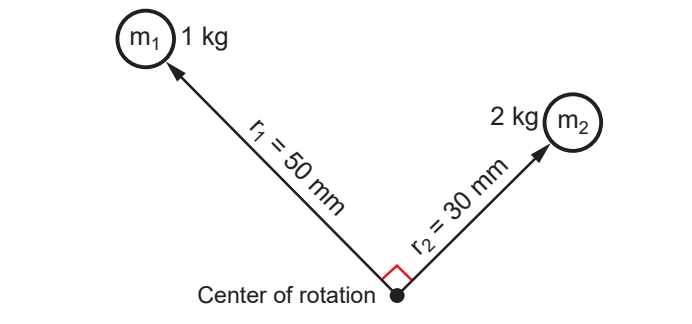
BALANCING MULTIPLE ROTATING MASSES

When balancing masses that are not diametrically opposite, one must consider the locations of the masses relative to each other and the centrifugal force created by each mass. A vector diagram of the centrifugal forces can then be used to determine the resultant, which becomes the counterbalancing centrifugal force. This can be illustrated in Example 15.

Example 15

The directions of centrifugal forces for a mass of 1 kg at a radius of 50 mm from the center of rotation and a 2 kg mass at a radius of 30 mm, are at a 90° angle to each other, as shown in Figure 9. To balance these forces, what additional mass would be required at a radius of 45 mm and what would be its position?

Figure 9 – Unbalance with Dual Masses



Solution 15

Again, since all masses have the same angular velocity, we only need to consider the values of “ $m \times r$ ” for each mass, which are:

$$m_1 r_1 = 1 \text{ kg} \times 50 \text{ mm} = 50 \text{ kg mm}$$

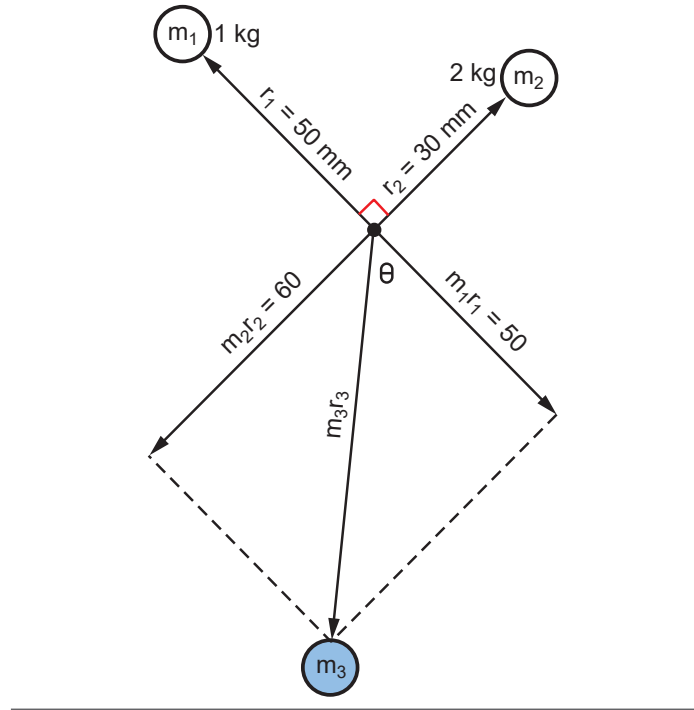
and

$$m_2 r_2 = 2 \text{ kg} \times 30 \text{ mm} = 60 \text{ kg mm}$$

We can now construct a vector diagram of these “ $m \times r$ ” values, with each vector representing the counterbalance for its respective mass.

For illustration, this vector diagram is added to Figure 9, as shown in Figure 10.

Figure 10 – Vector Solution to Balance Two Masses



The resultant, $m_3 r_3$, can now be calculated as follows:

$$\begin{aligned} m_3 r_3 &= \sqrt{(m_1 r_1)^2 + (m_2 r_2)^2} \\ &= \sqrt{(50 \text{ kg mm})^2 + (60 \text{ kg mm})^2} \\ &= \sqrt{2500 + 3600 \text{ kg}^2 \text{ mm}^2} \\ &= 78.1 \text{ kg mm} \end{aligned}$$

Given that it is 45 mm from the center of rotation, the magnitude of m_3 can be calculated by:

$$\begin{aligned} m_3 r_3 &= 78.1 \text{ kg mm} \\ m_3 &= \frac{78.1 \text{ kg mm}}{45 \text{ mm}} = 1.736 \text{ kg} \end{aligned}$$

The position of m_3 can be determined by trigonometry. (Refer to Figure 10)

$$\begin{aligned} \tan \theta &= \frac{60}{50} = 1.2 \\ \theta &= \tan^{-1} 1.2 = 50.2^\circ \end{aligned}$$

The required balancing mass, m_3 , at 45 mm radius, is **1.736 kg**, at an angle of $50.2 + 90 = 140.2^\circ$ from m_2 (Ans.)



CHAPTER QUESTIONS

1. What is the angular velocity of a flywheel rotating at 200 rpm?
2. Define moment of inertia and describe what is meant by the radius of gyration.
3. A rotational force of 50 N is applied to the rim of a wheel with a diameter of 2 m. What is the torque?
4. The mass of a flywheel is 125 kg and its radius of gyration is 400 mm. Calculate the kinetic energy stored when rotating at 150 and 350 rpm, respectively.
5. A crane engine lifts a 420 kg mass to a height of 10 m in 1.74 minutes. Indicated power of the engine is 416 W. What is the mechanical efficiency of the engine?
6. A pulley, 300 mm in diameter, is driven at 350 rpm by a belt 14 mm thick. Tensions in the tight and slack sides of the belt are 1800 and 500 N respectively. Considering the thickness of the belt, find the power transmitted.
7. Describe centripetal and centrifugal force and indicate the difference between them.
8. Find the change in height of a Watt governor when its speed increases from 80 rpm to 120 rpm.
9. A shaft is found to have an unbalance of 0.5 kg at a radius of 100 mm from the center rotation. At what radius and position in the same plane should a mass of 1 kg be placed for balance?





CHAPTER 10

Friction

LEARNING OUTCOME

When you complete this chapter you should be able to:

Perform calculations related to frictional force.

LEARNING OBJECTIVES

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

1. *Describe the concept, types, and laws of friction.*
2. *Define and calculate the coefficient of friction and applied forces for objects moved on a horizontal surface by forces parallel to the surface.*
3. *Define and calculate the applied forces for objects moved on a horizontal surface by forces not parallel to the surface.*
4. *Define and calculate the applied forces for objects moved on an inclined plane.*
5. *Define and calculate the frictional forces on a screw jack.*
6. *Define and calculate maximum torque on a belt drive.*



OBJECTIVE 1

Describe the concept, types, and laws of friction.

CONCEPT OF FRICTION

Whenever the surface of one body is in contact with the surface of another, there is a force that prevents or inhibits relative motion. This force is called friction. It acts in a direction opposite to motion and parallel to the contacting surfaces.

Friction is important in all types of machinery because it absorbs power that is not recoverable. For example, in an automobile, around 20% of the power is used to counteract friction forces in the engine, power train and wheels. The work done by friction forces is normally dissipated as heat.

Friction keeps a belt from slipping on a pulley so that power can be transmitted. Without friction between wheels and the road, a vehicle would not be able to move. It also prevents objects from moving on surfaces where the angle is not excessive.

When forces are removed from a sliding object, friction ensures that it will come to a stop. However, this also means that a force must be applied to start an object moving on a surface.

TYPES OF FRICTION

Friction is the resistance to motion. It exists regardless of whether there is relative motion between contacting surfaces.

Static friction is the force exerted between two bodies that are not moving relative to each other.

Sliding (or kinetic) friction is the force acting against the direction of motion and parallel to the two surfaces while they are moving relative to each other. The coefficient of kinetic friction is less than the coefficient of static friction. This means that it takes more force to start a body sliding than it does to keep the body sliding.

Limiting friction is the maximum force necessary to overcome static friction and to cause sliding motion.

Rolling friction is the resistance to motion when a wheel rolls along a surface. The coefficient of rolling friction is usually about 1% that of sliding friction. Wheels and other round objects will roll along the ground much more easily than they will slide along it.

Fluid friction occurs when there is resistance to motion in a fluid. This is evident in situations such as lubrication of bearings.

Internal friction can also occur in solids, such as rubber, that are easily deformable. It causes an increase in the temperature of the object.

LAW OF FRICTION

A number of laws govern the behaviour of friction.

1. Both sliding and limiting friction are proportional to the normal (or perpendicular) force which presses the two surfaces together.
2. The force of friction depends on the type and roughness of the two surfaces.
3. The amount of friction is independent of the area of contact.
4. Friction is essentially independent of sliding speed at low speeds. At higher speeds, the surface temperature increases, due to heating, and a decrease in friction may occur.



OBJECTIVE 2

Define and calculate the coefficient of friction and applied forces for objects moved on a horizontal surface by forces parallel to the surface.

PARALLEL FORCES

Coefficients of Friction

Since friction is a sum of the normal (also called loading) force and any resultant forces acting parallel to the surfaces, it is possible to define a coefficient of friction that is the ratio of these two forces.

The **coefficient of sliding friction** μ (pronounced “mew”) is found experimentally and applies to a specific set of surfaces. It is defined as:

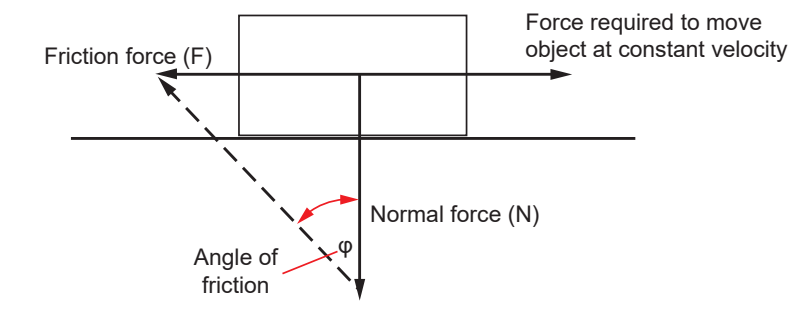
$$\mu = \frac{F}{N}$$

Where F is the friction force that balances the force acting on an object while it slides at a constant velocity, and N is the normal force that presses the two surfaces together. The forces for a simple block moving on a horizontal surface are shown in Figure 1.

The same equation defines **coefficient of static friction** except that the friction force F is the limiting force or the maximum static friction force just before sliding motion commences. It is also determined experimentally.

Because the units for F and N are the same (Newtons), the coefficient of friction has no units.

Figure 1 – Forces Related to Friction



The vector resultant of the two forces, F and N , produces an angle that is called the angle of friction or the **friction angle**. From Figure 1, it can be seen that:

$$\tan \phi = \frac{F}{N}$$

However, since the coefficient of friction also equals F/N ($\mu = \frac{F}{N}$) it follows that $\tan \phi$ is equal to the coefficient of friction or:

$$\tan \phi = \mu$$

Example 1

A mass of 50 kg slides along a horizontal plane at uniform velocity. If the coefficient of friction is 0.2, what force is required to move the mass at constant velocity and what is the friction angle?

Solution 1

Normal force is calculated using the equation:

$$\begin{aligned} F &= mg \\ &= 50 \text{ kg} \times 9.81 \text{ N/kg} \\ &= 490.5 \text{ N} \end{aligned}$$

From equation $\mu = \frac{F}{N}$, the force required to move the object at constant velocity is the same as the friction force so that:

$$\begin{aligned} F &= \mu N \\ &= 0.2 \times 490.5 \text{ N} \\ &= \mathbf{98.1 \text{ N (Ans.)}} \end{aligned}$$

Friction angle is found using the equation, $\tan \phi = \mu$:

$$\begin{aligned} \tan \phi &= \mu \\ \tan \phi &= 0.2 \\ \phi &= \tan^{-1} 0.2 \\ &= \mathbf{11.31^\circ \text{ (Ans.)}} \end{aligned}$$

Example 2

A 100 kg object is to slide on a horizontal plane. If the coefficient of static friction is 0.3 and the coefficient of sliding friction is 0.2, what is the force required to start the object moving and the force required to keep it sliding at a constant velocity?

Solution 2

Normal force is calculated using the equation:

$$\begin{aligned} N &= mg \\ &= 100 \text{ kg} \times 9.81 \text{ N/kg} \\ &= 981 \text{ N} \end{aligned}$$

From equation $\mu = \frac{F}{N}$ the force required to start the object moving is:

$$\begin{aligned} F &= \mu N \\ &= 0.3 \times 981 \text{ N} \\ &= \mathbf{294.3 \text{ N (Ans.)}} \end{aligned}$$

From equation $\mu = \frac{F}{N}$ the force required to move the object at constant velocity is:

$$\begin{aligned} F &= \mu N \\ &= 0.2 \times 981 \text{ N} \\ &= \mathbf{196.2 \text{ N (Ans.)}} \end{aligned}$$



OBJECTIVE 3

Define and calculate the applied forces for objects moved on a horizontal surface by forces not parallel to the surface.

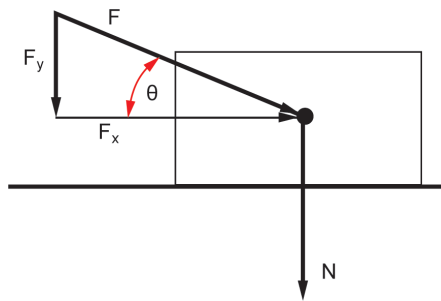
NON-PARALLEL FORCES

Applied Forces

The force applied to move an object may not be parallel to the surfaces, so additional calculations have to be done to resolve the vectors.

If a pushing force, F , is applied at a downward angle, as shown in Figure 2, the normal force (ie. the perpendicular force between the object and the surface) will include not only the gravitational force, W , due to the mass of the object, but also the vertical component, F_y , of the applied force. The force available to overcome friction is the horizontal component, F_x , of the applied force.

Figure 2 – Non-parallel Force Acting Downwards



The vector equations for the applied force become:

$$\sin \theta = \frac{F_y}{F}$$

$$F_y = F \sin \theta$$

$$F_x = F \cos \theta$$

The applicable version of the equation, $F = \mu N$ becomes:

$$F_x = \mu(W + F_y)$$

Substituting equations $F_y = F \sin \theta$ into equation $F_x = F \cos \theta$, the force required to overcome friction and move an object at a constant velocity becomes:

$$F_x = \mu(W + F_y)$$

$$F \cos \theta = \mu(W + F \sin \theta)$$

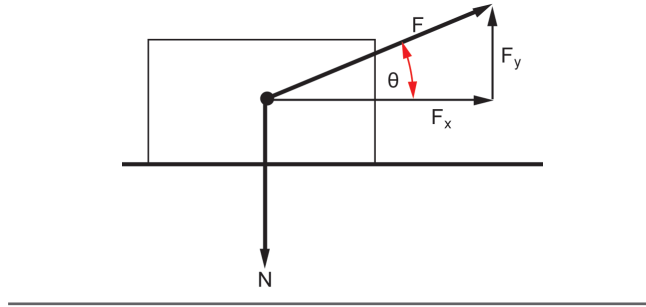
$$F \cos \theta = \mu W + \mu F \sin \theta$$

$$F \cos \theta - \mu F \sin \theta = \mu W$$

$$F = \frac{\mu W}{(\cos \theta - \mu \sin \theta)}$$

If an upwards force is applied as shown in Figure 3, the vertical component of the applied force decreases the normal force. The force available to overcome friction is still the horizontal component of the applied force.

Figure 3 – Non-parallel Force Acting Upwards



The vector equations for the applied force are the same as those shown in equations $F_y = F \sin \theta$ and $F_x = F \cos \theta$.

In this case, the applicable version of equation $F = \mu N$ becomes:

$$F_x = \mu(W - F_y)$$

The force required to overcome friction and move an object at a constant velocity becomes:

$$F = \frac{\mu W}{(\cos \theta + \mu \sin \theta)}$$

Example 3

A force is applied at an angle of 30° downwards on an object of mass 40 kg. If the coefficient of sliding friction is 0.5, what is the force required to keep it sliding at a constant velocity?

Solution 3

Normal force due to the mass is calculated using the equation:

$$\begin{aligned} W &= mg \\ &= 40 \text{ kg} \times 9.81 \text{ N/kg} \\ &= 392.4 \text{ N} \end{aligned}$$

The required force is obtained from equation $F = \frac{\mu W}{(\cos \theta - \mu \sin \theta)}$

$$\begin{aligned} F &= \frac{\mu W}{(\cos \theta - \mu \sin \theta)} \\ &= \frac{0.5 \times 392.4 \text{ N}}{\cos 30^\circ - 0.5 \sin 30^\circ} \\ &= \frac{196.2 \text{ N}}{0.866 - 0.25} \\ &= 318.5 \text{ N(Ans.)} \end{aligned}$$



Example 4

A force is applied at an angle of 30° upwards on an object of mass 40 kg. If the coefficient of sliding friction is 0.5, what is the force required to keep it sliding at a constant velocity?

Solution 4

The normal force due to the mass is calculated using the equation:

$$\begin{aligned} W &= mg \\ &= 40 \text{ kg} \times 9.81 \text{ N/kg} \\ &= 392.4 \text{ N} \end{aligned}$$

The required force is obtained from equation $F = \frac{\mu W}{(\cos \theta + \mu \sin \theta)}$

$$\begin{aligned} F &= \frac{\mu W}{(\cos \theta + \mu \sin \theta)} \\ &= \frac{0.5 \times 392.4 \text{ N}}{\cos 30^\circ + 0.5 \sin 30^\circ} \\ &= \frac{196.2 \text{ N}}{0.866 + 0.25} \\ &= 175.8 \text{ N (Ans.)} \end{aligned}$$

OBJECTIVE 4

Define and calculate the applied forces for objects moved on an inclined plane.

FORCES ON AN INCLINED PLANE

When an object rests on an inclined plane, the force of static friction counteracts the force of gravity. As long as the angle of the incline is not too great, the object remains at rest. If the incline is slowly increased, the object starts to slide at a certain angle, called the **angle of repose**. From Figure 4, it can be seen that, at the point of initial motion, the limiting friction force must equal the force that gravity imposes on the object, so that:

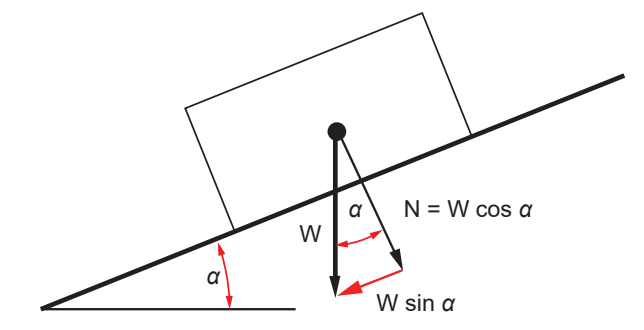
$$\mu W \cos \alpha = W \sin \alpha$$

$$\mu = \frac{\sin \alpha}{\cos \alpha}$$

$$\mu = \tan \alpha$$

The coefficient of static friction can be determined using the angle of repose. The coefficient of static friction is independent of the mass of the object.

Figure 4 – Object on Incline in Equilibrium



Raising the incline can also determine the coefficient of sliding friction except that the object needs to be tapped lightly to overcome the limiting force. The incline is increased until the object remains sliding.

Forces While Sliding Up an Inclined Plane

If the object is required to slide up an inclined plane, the total force applied must overcome both the force of friction and the force of gravity. Figure 5 illustrates the forces applied.

$$\begin{aligned} \text{Force of friction} &= \mu \times N \\ &= \mu W \cos \alpha \end{aligned}$$

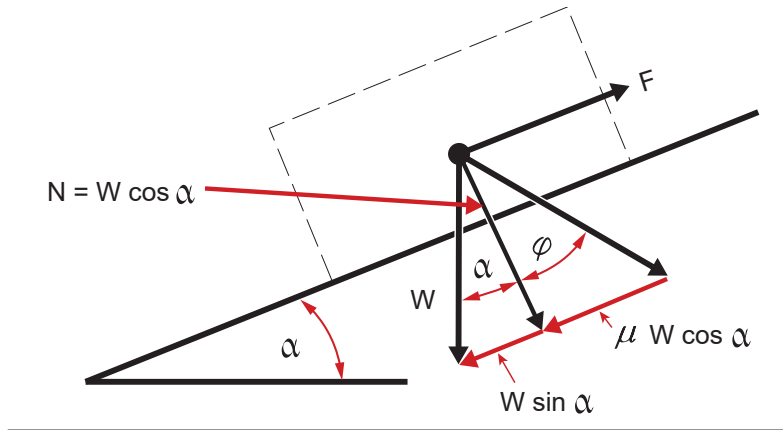
$$\text{Force due to gravity} = W \sin \alpha$$

Total force required to move the object up the plane is the sum of the two forces so that:

$$F = W \sin \alpha + \mu W \cos \alpha$$



Figure 5 – Forces Applied to an Object on an Incline



Forces While Sliding Down an Inclined Plane

If the object is to slide down the plane at a uniform velocity, the force of gravity will assist in overcoming the frictional force and a smaller force is needed to move the object. The equation for the required force becomes:

$$F = \mu W \cos \alpha - W \sin \alpha$$

A force is required only if the angle of incline is less than the angle of repose.

Keeping an Object from Sliding Down an Inclined Plane

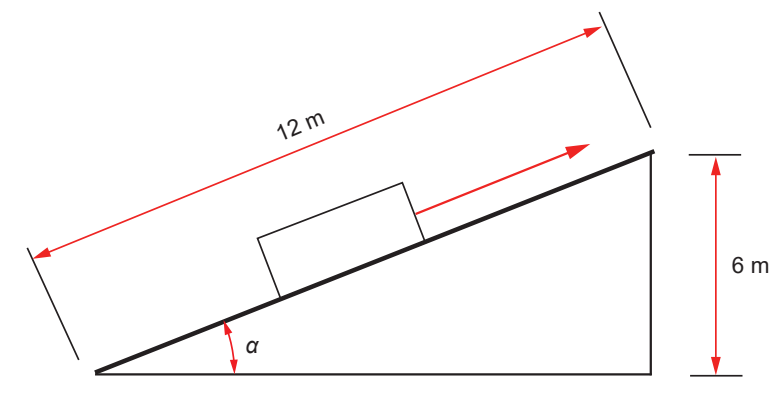
If the angle of incline is greater than the angle of repose, a force is required to keep it stationary. This force can be calculated from the equation:

$$F = W \sin \alpha - \mu W \cos \alpha$$

Example 5

A rope, parallel to the plane, pulls a 90 kg object up an inclined plane that is 12 m long and 6 m high (Figure 6). If the coefficient of sliding friction is 0.3, what is the force required to move the object at a constant velocity?

Figure 6 – Inclined Plane



Solution 5

Angle of the incline is:

$$\sin \alpha = \frac{6}{12}$$

$$\alpha = 30^\circ$$

Force that gravity imposes is calculated as:

$$W = m g$$

$$= 90 \text{ kg} \times 9.81 \text{ N/kg}$$

$$= 882.9 \text{ N}$$

Force to move the object up the plane is found using equation $F = W \sin \alpha + \mu W \cos \alpha$:

$$F = W \sin \alpha + \mu W \cos \alpha$$

$$= 882.9 \text{ N} \times \sin 30^\circ + 0.3 \times 882.9 \text{ N} \times \cos 30^\circ$$

$$= \mathbf{670.83 \text{ N (Ans.)}}$$

Example 6

A 100 kg object rests on a plane, which is inclined at 12° to the horizontal. If the coefficient of sliding friction is 0.32, what is the force required to move the object at constant velocity a) up the plane and b) down the plane and c) what is the angle of repose?

Solution 6

The force gravity imposes is calculated as:

$$W = m g$$

$$= 100 \text{ kg} \times 9.81 \text{ N/kg}$$

$$= 981 \text{ N}$$

a) The force to move the object up the plane is found using equation

$$F = W \sin \alpha + \mu W \cos \alpha:$$

$$F = W \sin \alpha + \mu W \cos \alpha$$

$$= 981 \text{ N} \times \sin 12^\circ + 0.32 \times 981 \text{ N} \times \cos 12^\circ$$

$$= \mathbf{511.0 \text{ N (Ans.)}}$$

b) The force to move the object down the plane is found using equation

$$F = \mu W \cos \alpha - W \sin \alpha:$$

$$F = \mu W \cos \alpha - W \sin \alpha$$

$$= 0.32 \times 981 \text{ N} \times \cos 12^\circ - 981 \text{ N} \times \sin 12^\circ$$

$$= \mathbf{103.1 \text{ N (Ans.)}}$$



c) The angle of repose is found using equation, $\mu = \tan \alpha$

$$\begin{aligned}\tan \alpha &= \mu \\ &= 0.32 \\ \alpha &= \tan^{-1} 0.32 \\ &= 17.75^\circ \text{ (Ans.)}\end{aligned}$$

Example 7

A 50 kg object rests on a ramp that is inclined at 15° to the horizontal. If the coefficient of sliding friction is 0.25, what force, if any, applied parallel to the ramp, is required to prevent the object from sliding down the ramp?

Solution 7

Vertical downward force due to gravity:

$$\begin{aligned}W &= mg \\ &= 50 \text{ kg} \times 9.81 \text{ N/kg} \\ &= 490.5 \text{ N}\end{aligned}$$

Gravitational force parallel to the ramp:

$$\begin{aligned}F &= W \sin \alpha \\ &= 490.5 \text{ N} \times \sin 15^\circ \\ &= 126.94 \text{ N}\end{aligned}$$

Friction force is:

$$\begin{aligned}F &= \mu W \cos \alpha \\ &= 0.25 \times 490.5 \text{ N} \times \cos 15^\circ \\ &= 118.45 \text{ N}\end{aligned}$$

Because the force due to gravity is greater than the friction force, the object will slide downwards if unrestrained. Force required to hold the object is:

$$\begin{aligned}F &= \text{force of gravity} - \text{friction force} \\ &= 126.94 - 118.45 \\ &= 8.49 \text{ N (Ans.)}\end{aligned}$$

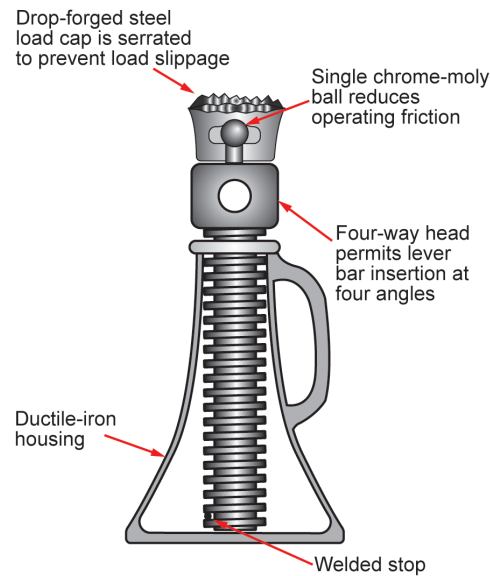
OBJECTIVE 5

Define and calculate the frictional forces on a screw jack.

FORCES ON A SCREW JACK

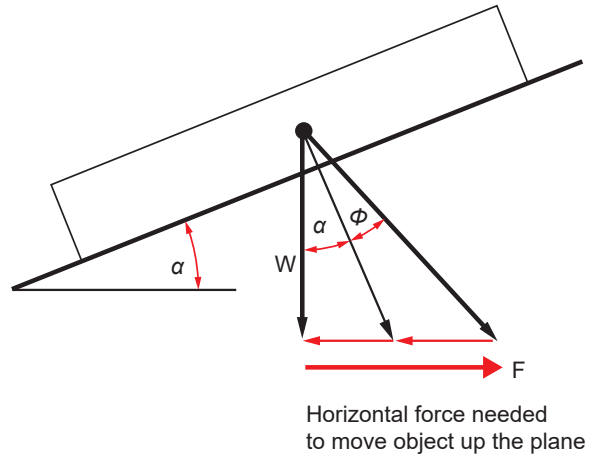
One application of the principle of forces on an inclined plane involves a screw jack (see Figure 7). This consists of a screw-operated jack for lifting, exerting pressure, or adjusting position (as of a machine part)

Figure 7 – Screw Jack



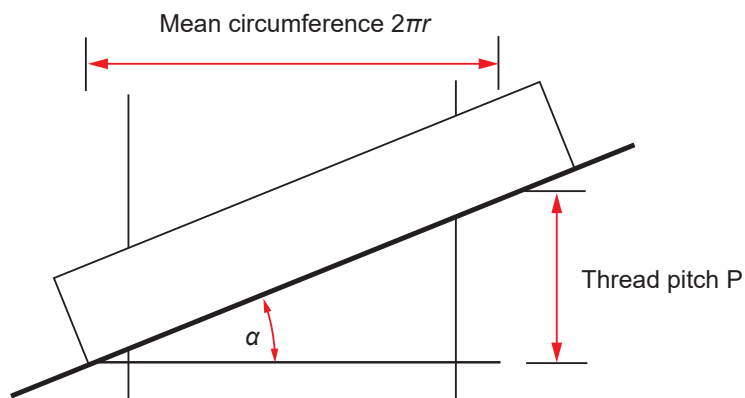
(Courtesy of L.K. Goodwin Co.)

The screw acts as the inclined plane, against which a force is applied. It is assumed here that the screw jack is vertical so that the force of gravity acts as shown in Figure 8. The difference between the screw jack and an object moving up a plane is that the force on a screw jack is applied horizontally, usually by a handle at a known radius, to gain mechanical advantage.


Figure 8 – Forces Applicable to a Screw Jack


The angle of the incline can be determined from the thread pitch and the mean circumference (see Figure 9) using the equation:

$$\alpha = \tan^{-1} \frac{P}{2\pi r}$$

Figure 9 – Calculating Tread Pitch Angle


To move the screw jack upwards, the horizontal force required is the sum of the gravitational and friction forces, which can be seen from Figure 8, to result in the equation:

$$F = W \tan (\alpha + \phi)$$

To move the screw jack downwards, the horizontal force required is the difference between the force of friction and the gravitational force, so the equation becomes:

$$F = W \tan(\phi - \alpha)$$

A small pitch thread makes the angle of the thread smaller than the angle of friction and thus a safer screw jack. It also makes it easier to turn due to the lower required force, but more turns are required.

Example 8

A screw jack is used to lift a mass of 2 tonnes. The pitch of the thread is 10 mm with a mean diameter of 5 cm and the coefficient of friction is 0.2. What horizontal force is required with a lever of 0.75 m to lift the load?

Solution 8

Force of the mass due to gravity is:

$$\begin{aligned} W &= mg \\ &= 2000 \text{ kg} \times 9.81 \text{ N/kg} \\ &= 19\,620 \text{ N} \end{aligned}$$

Angle of the thread is calculated from equation $\alpha = \tan^{-1} \frac{P}{2\pi r}$ as:

$$\begin{aligned} \alpha &= \tan^{-1} \frac{P}{2\pi r} \\ &= \tan^{-1} \frac{10 \text{ mm}}{2\pi \times 25 \text{ mm}} \\ &= 3.64^\circ \end{aligned}$$

Angle of friction comes from equation $\mu = \tan \alpha$:

$$\begin{aligned} \mu &= \tan \alpha \\ \alpha &= \tan^{-1} \mu \\ &= \tan^{-1} 0.2 \\ &= 11.3^\circ \end{aligned}$$

Force needed at the mean radius is computed using equation $F = W \tan (\alpha + \phi)$:

$$\begin{aligned} F &= W \tan(\alpha + \phi) \\ &= 19\,620 \text{ N} \times \tan (3.64 + 11.3) \\ &= 5235 \text{ N} \end{aligned}$$

Taking the ratio between the mean radius and the radius of the lever calculates the force with a lever. This means that actual force required is:

$$\begin{aligned} F &= 5235 \text{ N} \times \frac{25 \text{ mm}}{750 \text{ mm}} \\ &= 174.5 \text{ N (Ans.)} \end{aligned}$$



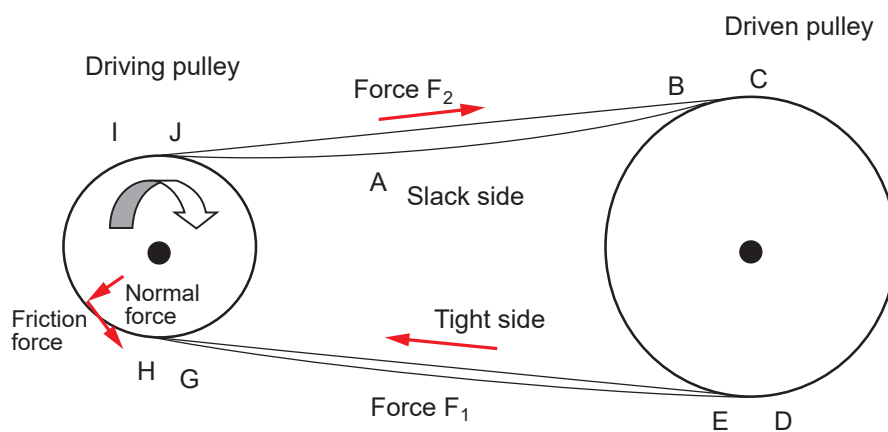
OBJECTIVE 6

Define and calculate maximum torque on a belt drive.

BELT DRIVES AND FRICTION

Belt drives depend on friction between the belt and the pulleys to prevent slippage so that power can be transmitted to the driven pulley. It is possible to calculate the maximum torque before the belt starts to slip. Figure 10 shows the geometry of a belt and pulley system.

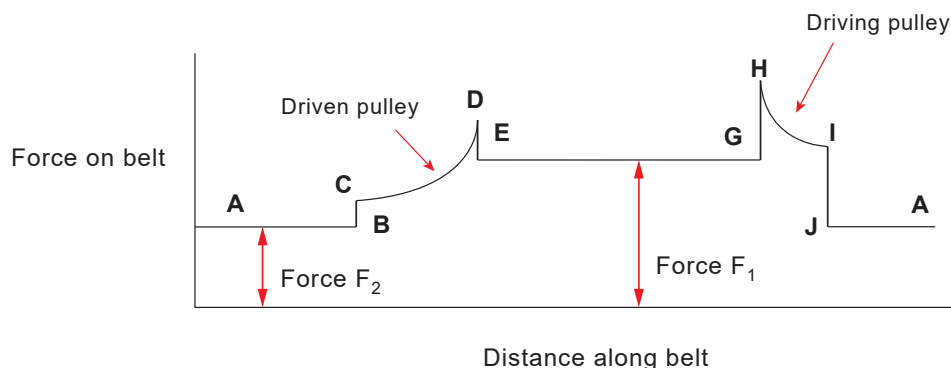
Figure 10 – Belt and Pulley Forces



The force on the tight side is higher than on the slack side. The difference between the two forces, $F_1 - F_2$, is the torque transmitted from the driving wheel and also determines the friction forces applied. Putting tension on the belt prior to operation assists with increasing the normal force available for friction. However, excessive pre-tension decreases the life of the belt because it is continually stretched and released as it passes around the pulleys.

It is interesting to note the change in the forces on the belt. Figure 11 shows how the force varies as the belt moves from the tight side to the driving pulley and then to the slack side. There are sharp increases in the tension as the belt moves onto each pulley and frictional force is applied. When the belt leaves the pulley, there is a corresponding decrease in tension.

Figure 11 – Forces on a Belt



The maximum force allowed before slippage occurs is defined using the equation:

$$F_1 = F_2 e^{\mu \alpha}$$

Where

F_1 = tension of tight side, N

F_2 = tension of slack side, N

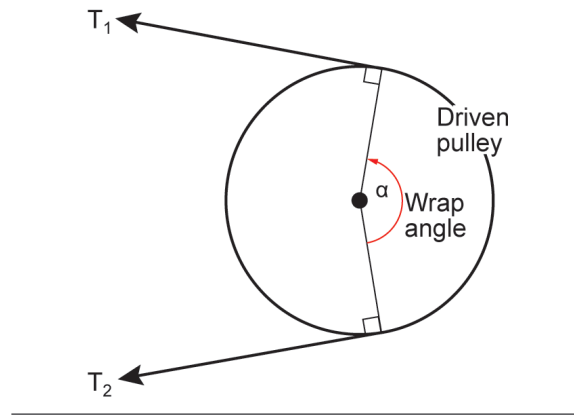
μ = coefficient of friction

α = angle of wrap, radians

e = 2.718 (base of natural logarithm)

Note: The “wrap angle” is the angle, in radians, formed at the center of the pulley between the perpendiculars drawn to the center from the belt tangents on opposite sides of the pulley.

Figure 12 – Wrap Angle



Example 9

A belt with a 0.5 coefficient of friction drives a pulley with a diameter of 50 cm. Force on the tight side is 1000 N. Assuming that the belt wraps around half of the pulley, what is the maximum torque allowed?

Solution 9

Since there are 2π radians in a circle, wrap angle is π radians. Slack side is determined using equation $F_1 = F_2 e^{\mu \alpha}$:

$$F_1 = F_2 e^{\mu \alpha}$$

from which

$$\begin{aligned} F_2 &= \frac{F_1}{e^{\mu \alpha}} \\ &= \frac{1000 \text{ N}}{e^{0.5 \times \pi}} \\ &= \frac{1000 \text{ N}}{(2.718)^{1.571}} \\ &= \frac{1000 \text{ N}}{4.8097} \\ &= 207.91 \text{ N} \end{aligned}$$

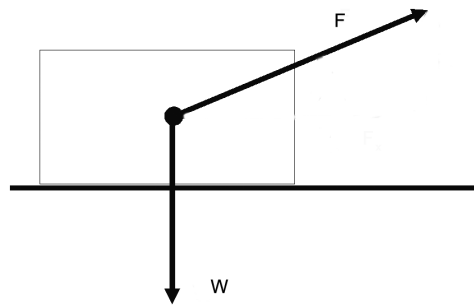


Therefore, maximum torque before slippage is:

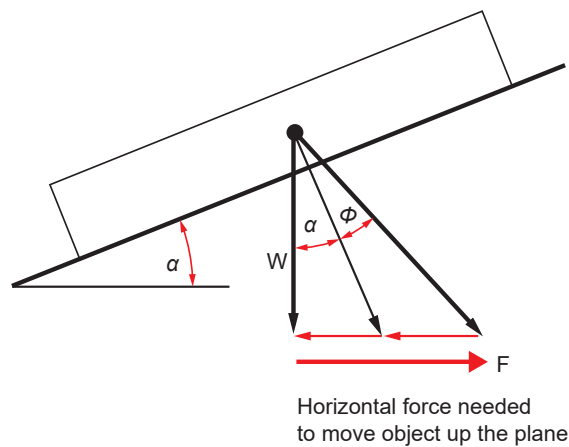
$$\begin{aligned} T &= (F_1 - F_2) \times r \\ &= (1000 \text{ N} - 207.91 \text{ N}) \times 0.25 \text{ m} \\ &= 702.09 \text{ N} \times 0.25 \text{ m} \\ &= \mathbf{198 \text{ Nm (Ans.)}} \end{aligned}$$

CHAPTER QUESTIONS

1. Define static and sliding friction and indicate which is greater.
2. Define the coefficient of friction by stating the equation. Illustrate forces with a diagram for a simple block moving on a horizontal surface.
3. A mass of 100 kg slides along a horizontal plane at uniform velocity. If the coefficient of friction is 0.1, what is the force required to move the mass?
4. Using the standard equation for the coefficient of friction, derive the equation for an upwards force acting on a sliding object as shown in the diagram below. Illustrate forces on the diagram.



5. Define the angle of repose and state the equation that relates it to the coefficient of friction.
6. Using the diagram below, derive the equation for the horizontal force required to move a jack screw upwards.





Static and Dynamic Forces

LEARNING OUTCOME

When you complete this chapter you should be able to:

Perform calculations related to static and dynamic forces acting on a body.

LEARNING OBJECTIVES

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

1. *Define and evaluate forces in terms of moments and couples.*
2. *Define and calculate centroids and first and second moments of areas.*
3. *Define and calculate the different types of stress.*
4. *Define strain, modulus of elasticity, Poisson's ratio and perform calculations.*
5. *Define the thermal expansion of bars, including reactions, under conditions of restricted expansion and reactions of bars composed of dissimilar metals.*
6. *Define and calculate shear forces and bending moments for simply supported beams and cantilevers.*
7. *Perform calculations involving the fundamental torsion equation and explain the relationship between torque and stress.*
8. *Explain the relationship between torque and power, and calculate maximum and mean torque for solid shafts of circular cross section.*
9. *Calculate stress in coupling bolts due to torque.*



OBJECTIVE 1

Define and evaluate forces in terms of moments and couples.

STATICS AND DYNAMICS

The mechanics of rigid bodies is divided into two areas: statics and dynamics. Statics is the study of forces acting on a body that is at rest or moving at a uniform velocity. Dynamics is the study of the forces acting on a moving body that is accelerating or decelerating.

MOMENTS

A **moment** of a force is a measure of the tendency of a body to rotate about a specific point or axis when the force is applied to it. A moment is identified by both its magnitude and direction, causing the affected body to tend to rotate in either a **clockwise** or an **anticlockwise** direction.

When two or more opposing forces, or their resulting moments, are in balance and their algebraic sum is zero, then the body in question is in **equilibrium** and there will be no change to its current state of motion. If it is stationary, it will remain so. If it is moving, it will continue to move at a constant velocity.

An imbalance in moments exists due to a force not having an equal and opposite force directly along its line of action. The moment of a force is the product of the force and its perpendicular distance from a relevant point.

An object is in equilibrium if the algebraic sum of all the forces or moments acting on it is zero. Even though the forces are in equilibrium, they may exist in different planes and directions. A useful way of evaluating these forces is to understand the moments that they create.

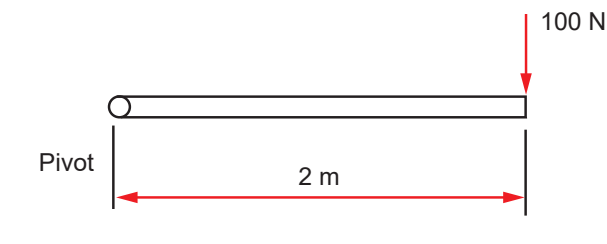
The moment, M (units are Newton-meters or Nm), is the product of force, F , and length, l (where l is the perpendicular distance from the pivot point under consideration to the direction of the force), which gives the equation:

$$M = F l$$

Example 1

What is the magnitude and direction of the moment caused by the vertical force of 100 N in Figure 1?

Figure 1 – Force Acting About a Pivot



Solution 1

From the equation $M = F l$, the moment is:

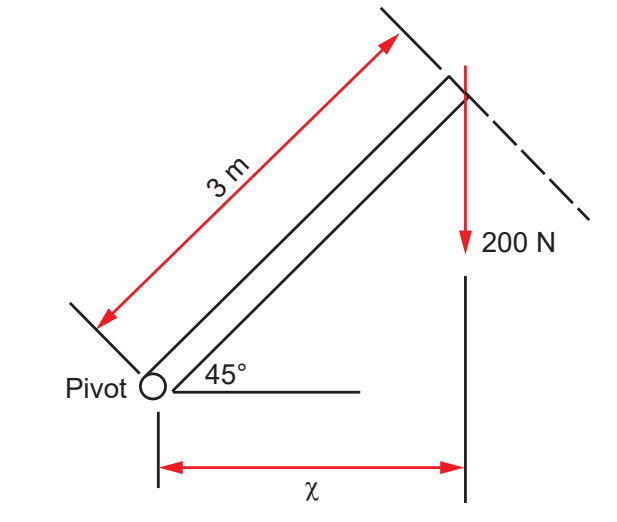
$$\begin{aligned} M &= F l \\ &= 100 \text{ N} \times 2 \text{ m} \\ &= \mathbf{200 \text{ Nm (Ans.)}} \end{aligned}$$

The moment acts in a clockwise direction.

Example 2

What is the magnitude and direction of the moment caused by the vertical force of 200 N in Figure 2?

Figure 2 – Force Acting About an Angled Pivot



Solution 2

First, find the perpendicular distance, x.

$$\begin{aligned} \cos A &= \frac{x}{h} \\ x &= h \times \cos A \\ &= 3 \text{ m} \times \cos 45^\circ \\ &= 3 \times 0.7071 \text{ m} \\ &= 2.12 \text{ m} \end{aligned}$$

Using the equation: $M = F l$, the moment is:

$$\begin{aligned} M &= F l \\ &= 200 \text{ N} \times 2.12 \text{ m} \\ &= \mathbf{424 \text{ Nm (Ans.)}} \end{aligned}$$

The moment is in a clockwise direction.



STATIC EQUILIBRIUM

Moments are useful to evaluate situations where there are multiple forces acting on an object. A system of forces is in equilibrium if the algebraic sums of the resultant forces and moments are balanced or their algebraic sum is zero. The directions of the forces can be chosen according to the most convenient orientation, but a logical approach is to assume that vertical, horizontal and rotational forces and moments are balanced.

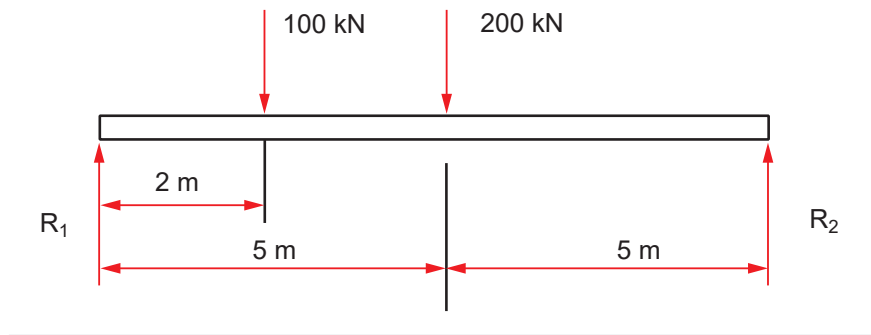
To establish equilibrium, find convenient sets of moments and build equations to ensure that:

1. The sum of vertical forces is zero.
2. The sum of horizontal forces is zero.
3. The sum of the clockwise moments equals the sum of the anticlockwise moments.

Example 3

A simply supported beam is loaded as shown in Figure 3. What are the required supporting forces, R_1 and R_2 , to maintain the beam in equilibrium?

Figure 3 – Simply Supported Beam



Solution 3

Convenient places to take moments are around the supports, located at R_1 and R_2 . For R_1 , the equation is:

Taking moments around the support at R_1 :

$$\text{clockwise moment} = \text{anticlockwise moment}$$

$$(100 \text{ kN} \times 2 \text{ m}) + (200 \text{ kN} \times 5 \text{ m}) = R_2 \text{ kN} \times 10 \text{ m}$$

$$R_2 = \frac{(100 \text{ kNm} \times 2 \text{ m}) + (200 \text{ kNm} \times 5 \text{ m})}{10 \text{ m}}$$

$$= 20 \text{ kN} + 100 \text{ kN}$$

$$= \mathbf{120 \text{ kN (Ans.)}}$$

Taking the moments around the support at R_2 :

clockwise moment = anticlockwise moment

$$R_1 \text{ kN} \times 10 \text{ m} = (100 \text{ kN} \times 8 \text{ m}) + (200 \text{ kN} \times 5 \text{ m})$$

$$R_1 = \frac{800 \text{ kNm} + 1000 \text{ kNm}}{10 \text{ m}}$$

$$= 80 \text{ kN} + 100 \text{ kN}$$

$$= 180 \text{ kN (Ans.)}$$

Looking at the vertical forces (there no horizontal forces).

verticle forces downwards = vertical forces upwards

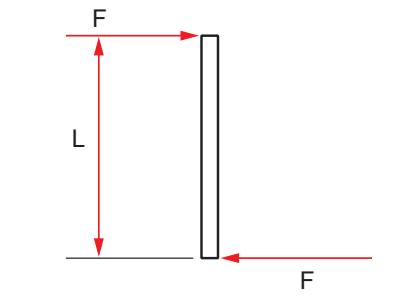
$$100 \text{ kN} + 200 \text{ kN} = 120 \text{ kN} + 180 \text{ kN}$$

$$300 \text{ kN} = 300 \text{ kN (Ans.)}$$

COUPLES

A couple has two parallel forces that are equal in magnitude, opposite in direction, and separated by a perpendicular distance. The net effect is a rotational force around the midpoint between the forces, as shown in Figure 4.

Figure 4 – Couple



The distance L is called the arm of the couple and the resultant moment is defined as:

$$M = FL$$

An example of a couple is a tire wrench with opposite handles. Since the forces are equal but opposite, a higher turning moment can be exerted on a wheel nut as compared to a single-sided wrench.

Example 4

Similar to Figure 4, two forces of 100 kN each are applied with a distance of 3 m between them. What is the resultant turning force?

Solution 4

Turning moment is found from equation $M = FL$:

$$M = FL$$

$$= 100 \text{ kN} \times 3 \text{ m}$$

$$= 300 \text{ kNm (Ans.)}$$



OBJECTIVE 2

Define and calculate centroids and first and second moments of areas.

CENTROIDS AND FIRST MOMENT OF AREA

The centroid of a two dimensional object is its geometric center. For symmetrical shapes, the centroid is easy to locate. For example, the centre of a circle is also its centroid. For a rectangle, the centroid is the point in the middle, where the two diagonals cross.

For irregular shapes, it is more difficult to find the centroid. A method called the first moment of areas can be used to find it. The first moment of area is defined as:

$$\text{First moment of area (about a point)} = \text{area} \times \text{distance (from the point)}$$

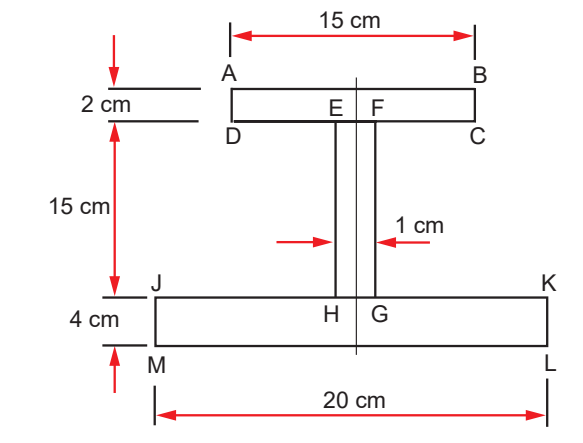
For irregular shapes, the centroid is located by dividing the shape into smaller areas whose centroids are known and then calculating the algebraic sum of the moments of those component areas.

Where three-dimensional mass is considered, the centroid is known as the **centre of mass** or the **centre of gravity**. If the object has a consistent density, the centre of mass is at the same location as the centroid. The centroid is mainly associated with two dimensional geometric shapes, whereas the centre of mass refers to three dimensional objects with known mass.

Example 5

Find the centroid for the two-dimensional shape shown in Figure 5.

Figure 5 – Object Dimensions



Solution 5

Since the shape is symmetrical around the vertical axis, the centroid must lie somewhere along this line. The shape can be broken into three rectangles, ABCD, EFGH and JKLM. The centroid for each rectangle is the geometric centre of each one.

Choose a plane around which moments can be taken, for example the line ML. The distance from the centroid of each rectangle to the plane ML is:

- 20 cm for ABCD (centre of ABCD is 1 cm from top)
- 11.5 cm for EFGH (centre of EFGH is 7.5 cm from both EF and GH)
- 2 cm for JKLM (centre of JKLM is 2 cm from ML)

Using the equation, first moment of area = area $\times$ distance, the moments for each are around the line ML can be found as follows:

$$M_{ABCD} = (15 \text{ cm} \times 2 \text{ cm}) \times 20 \text{ cm} = 600 \text{ cm}^2 \times \text{cm}$$

$$M_{EFGH} = (15 \text{ cm} \times 1 \text{ cm}) \times 11.5 \text{ cm} = 172.5 \text{ cm}^2 \times \text{cm}$$

$$M_{JKLM} = (20 \text{ cm} \times 4 \text{ cm}) \times 2 \text{ cm} = 160 \text{ cm}^2 \times \text{cm}$$

$$\text{Total moment} = 600 + 172.5 + 160 = 932.5 \text{ cm}^2 \times \text{cm}$$

Now calculating the moment of the centroid, where “y” is the arbitrary distance from the centroid to the line ML:

$$\begin{aligned} \text{Total moment about ML} &= [(15 \text{ cm} \times 2 \text{ cm}) + (15 \text{ cm} \times 1 \text{ cm}) + (20 \text{ cm} \times 4 \text{ cm})] \times y \text{ cm} \\ &= (30 + 15 + 80) \text{ cm}^2 \times y \text{ cm} \\ &= 125 y \text{ cm}^2 \times \text{cm} \end{aligned}$$

Since the two moments must be equal in order to maintain equilibrium, the distance from ML to the centroid is:

$$\begin{aligned} 125 y \text{ cm}^3 &= 932.5 \text{ cm}^3 \\ y &= 7.46 \text{ cm (Ans.)} \end{aligned}$$

SECOND MOMENT OF AREA

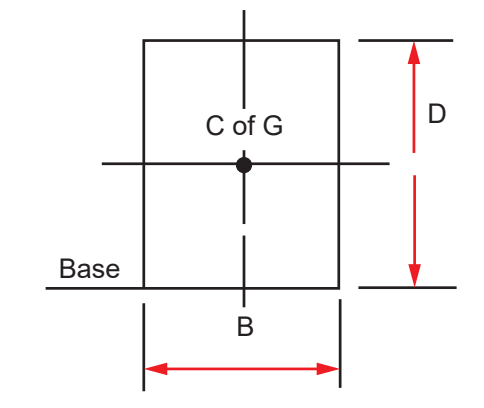
For certain beam calculations, it is necessary to determine a second moment of area, which includes the distance squared multiplied by the area, or:

$$\text{Second moment of area} = \text{area} \times \text{distance}^2$$

One application is in the design of shafts and beams to find their resistance to bending, and to torsion or twisting force. Torsion refers to the twisting stress on a shaft that an applied torque tends to create. When applied to angular motion, or rotation, the second moment of area is called the **moment of inertia** and the distance is called the **radius of gyration**.

Following are some examples of the second moment of area for a variety of shapes. The second moment of area is usually referred to by the letter I.

Figure 6 – Solid Rectangle





Second moment of area (or moment of inertia, I) for a solid rectangle (Figure 6) with respect to the centre of the rectangle is equal to I in the following equation:

$$\begin{aligned} I_{cg} &= \frac{\text{distance}^2 \times \text{area}}{12} \\ &= \frac{D^2 \times BD}{12} \\ &= \frac{BD^3}{12} \end{aligned}$$

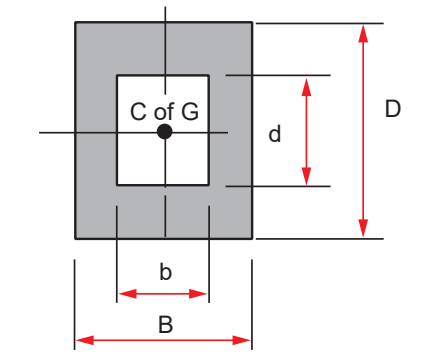
With respect to the base, it becomes

$$I_{\text{base}} = \frac{BD^3}{3}$$

Second moment of area or moment of inertia for a **hollow rectangle** (Figure 7) with respect to the centre of the rectangle is:

$$I_{cg} = \frac{BD^3 - bd^3}{12}$$

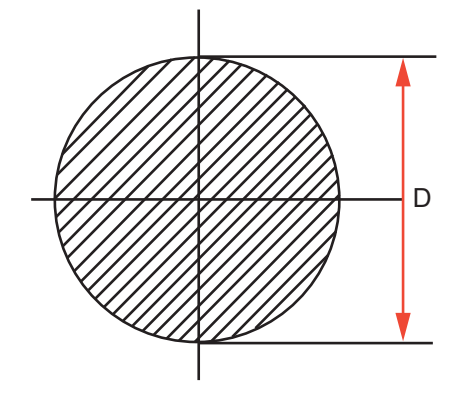
Figure 7 – Hollow Rectangle



Second moment of area or moment of inertia for a **solid circle** (Figure 8) with respect to the centre of the circle is:

$$I_{cg} = \frac{\pi D^4}{64}$$

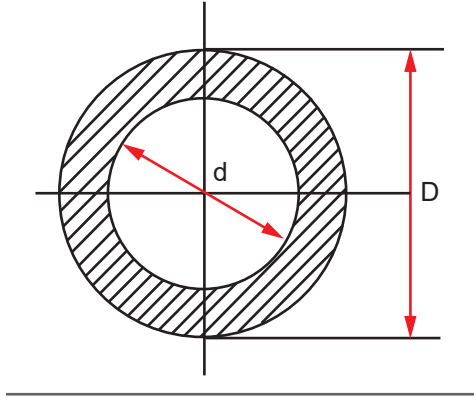
Figure 8 – Solid Circle



Second moment of area or moment of inertia for a **hollow circle** (Figure 9) with respect to the centre of the circle is

$$I_{cg} = \frac{\pi(D^4 - d^4)}{64}$$

Figure 9 – Hollow Circle





OBJECTIVE 3

Define and calculate the different types of stress.

TYPES OF LOAD

When external forces are applied to objects, there is an internal resistance set up in the material that opposes the external force. This resistance to the applied force is called **stress**. The applied external forces are referred to as **loads**, and different types of loads will cause different stresses to be generated in the object upon which the load is acting. Loads are classified according to the length of time they are applied, the area of application, and the type of stress they produce.

Loads can be classified according to the time period over which they are applied:

1. **Static load:** Load that is applied to an object very slowly and held at a constant magnitude so that equilibrium is reached. An example is the load on a building structure due to the mass of the building materials.
2. **Sustained load:** Load that is constant over a long period of time, such as the weight of a mass stored in a structure. The effects are usually the same as a static load except where the resistance to failure may differ due to specific stress or temperature conditions during loading.
3. **Impact load** or **shock load:** Load that is applied suddenly, in a very short time period. The load is dependent on both the mass and the velocity of the object producing the impact force. This may cause vibration which has to dampen before equilibrium is reached.
4. **Repeated load** or **cyclic load:** Load which increases and decreases in magnitude many times over specific periods of time, such as the opening and closing of engine valves.

Loads may also differ according to the area of application:

1. **Concentrated load:** Load that is applied to a small area relative to the total area, such as the wheel of a car on a road.
2. **Distributed load:** Load that is spread along a length or area, such as the weight of a beam.

Loads may be classified according to the type of stress they produce:

1. **Axial load:** The force acts through the centroid of the object so that no bending occurs. It produces uniform tension or compression across the affected area.
2. **Shear load:** The forces are parallel but not in the same plane, so that the stress varies across the cross-sectional area.
3. **Torsional load:** This type of load applies an angular moment or a twisting force to a beam or shaft.
4. **Bending load:** This occurs when a force is applied perpendicular to the axis of an object, such as the wind on a tower or loads on structural members.
5. **Thermal load:** This occurs when a change in temperature creates thermal expansion or contraction within an object that is physically constrained from moving freely.
6. **Combined load:** This is caused by more than one type of the above loads is applied to an object.

STRESS

The result of a load applied to an area is called stress. Stress is the internal resistance that results from the application of an external load. Stress is represented by the Greek symbol σ , or sigma.

$$\begin{aligned}\text{Direct stress} &= \frac{\text{load}}{\text{area}} \\ &= \frac{P}{A}\end{aligned}$$

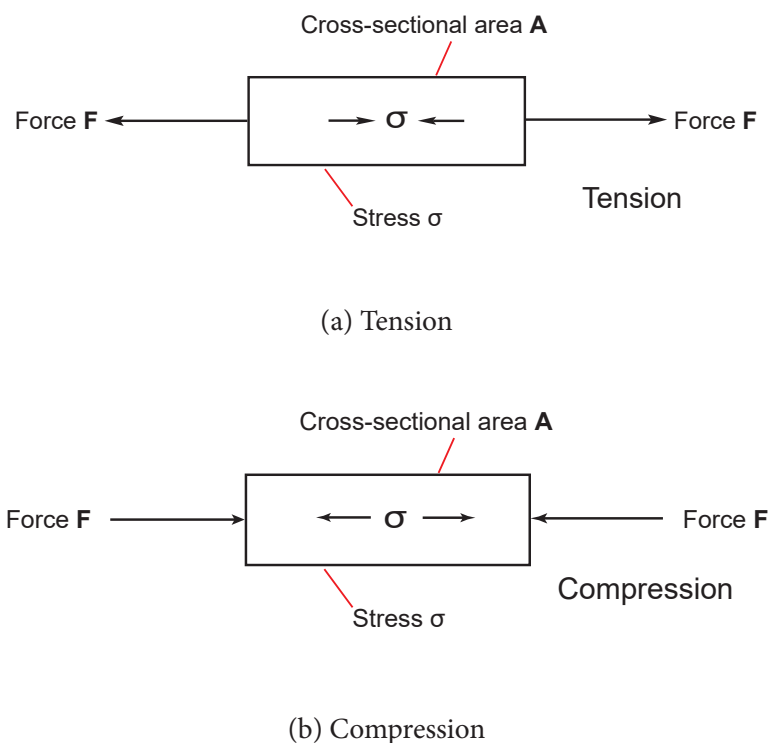
The units of stress are N/m^2 or Pascals (Pa).

Normally, stress calculations assume a constant cross-sectional area throughout the material being stressed. Since the amount of stress generated is inversely proportional to the cross-sectional area across which the load is distributed, it is very important to ensure that this assumption of uniform cross-sectional area is correct. Any reduction in cross-sectional area will cause an increase in the stress levels that are generated, and this could lead to material failure if they are not allowed for. When the area is not constant, the stress changes across the area produce regions of increased local stress or stress concentrations. These require specialized mathematical analysis and are often the cause of material failure of an object such as fracture or rupture.

TENSION AND COMPRESSION

Tension and compression are illustrated in Figure 10. When forces are in opposite directions in the same plane, there is tension in the object. It is said to be “in tension” and it is under tensile stress. When the forces are directed towards each other, the object is in compression and it is under compressive stress. In both cases, the distribution of stress is uniform.

Figure 10 – Tensile and Compressive Stresses





Example 6

A circular column with a diameter of 30 cm carries a compressive load of 100 kN. What is the stress on the column?

Solution 6

Area of the column is:

$$\begin{aligned} A &= \pi r^2 \\ &= \pi(0.15 \text{ m})^2 \\ &= 0.0707 \text{ m}^2 \end{aligned}$$

The stress as per the equation Direct stress = $\frac{P}{A}$ is:

$$\begin{aligned} \text{Direct stress} &= \frac{P}{A} \\ &= \frac{100 \text{ kN}}{0.0707 \text{ m}^2} \\ &= 1414.4 \text{ kPa (Ans.)} \end{aligned}$$

Example 7

A tie bar of 5 cm diameter is used in a structural framework. If maximum tensile stress is not to exceed 60 000 kPa, what is the maximum allowable load?

Solution 7

Area of the tie is

$$\begin{aligned} A &= \pi r^2 \\ &= \pi(0.025 \text{ m})^2 \\ &= 0.0020 \text{ m}^2 \end{aligned}$$

Rearranging the equation Direct stress = $\frac{P}{A}$, the maximum allowable force is:

$$\begin{aligned} \text{Direct stress} &= \frac{P}{A} \\ P &= (\text{Direct stress})A \\ &= 60\,000 \text{ kN/m}^2 \times 0.0020 \text{ m}^2 \\ &= 120.00 \text{ kN (Ans.)} \end{aligned}$$

SHEAR STRESS

Shear stress is produced by equal and opposite parallel forces (not in line with each other) that tend to make one part of the material slide over the other part. The stresses occur on plane sections that are parallel to the direction of the applied force, as shown in Figure 11.

Figure 11 – Shear Stress

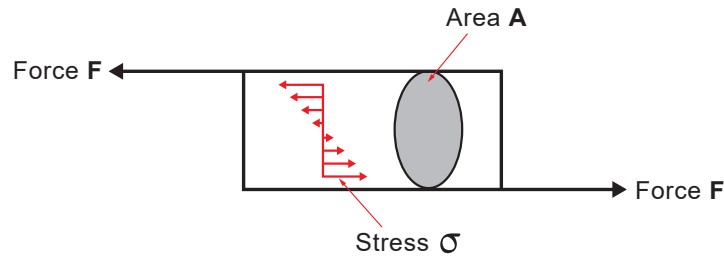
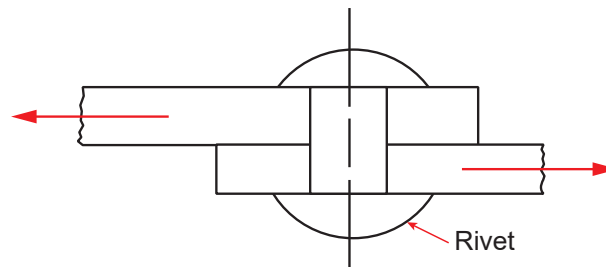


Figure 12 shows shear stress in a rivet. Because the stress is applied on one plane of the rivet, it is called single shear stress. The shear stress is calculated by dividing the force by the area of the rivet.

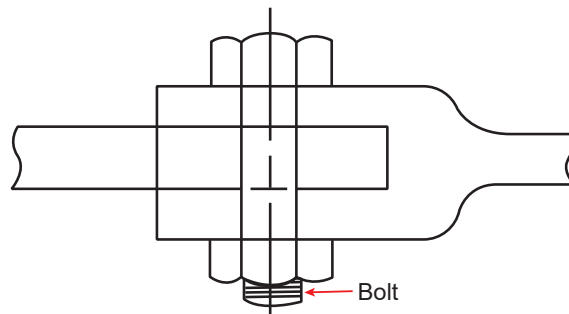
$$\text{Shear stress } (\tau) = \frac{\text{force}}{\text{area under shear}}$$

Figure 12 – Single Shear



In the example shown in Figure 13, the bolt experiences a shear force in two locations. The result is called double shear. Because the force is absorbed across two areas, the stress is calculated by dividing the force by twice the area of the bolt and the stress is thereby reduced in half.

Figure 13 – Double Shear



Note that the rivet and bolt in the above examples also experience bending and compressive stresses. Pure shear stress occurs only in torsion, or angular stress, which is covered in a later Objective.



Example 8

A bolt with a diameter of 1.5 cm connects two members so that the bolt is in double shear. If the load is 50 kN, what is the shear stress in the bolt?

Solution 8

Area of the bolt is:

$$\begin{aligned} A &= \pi r^2 \\ &= \pi(0.0075 \text{ m})^2 \\ &= 0.0002 \text{ m}^2 \end{aligned}$$

Area resisting the force is double the area of the bolt so that the shear stress is:

$$\begin{aligned} \text{Shear stress } (\tau) &= \frac{\text{force}}{\text{area under shear}} \\ &= \frac{50 \text{ kN}}{2 \times 0.0002 \text{ m}^2} \\ &= 125\,000 \text{ kPa or } 125 \text{ MPa (Ans.)} \end{aligned}$$

Table 1 – Table of Symbols

Sigma	σ	Direct Stress
Tau	τ	Shear Stress
Epsilon	ϵ	Direct Strain
Mu	μ	Poisson's Ratio
	E	Modulus of Elasticity

OBJECTIVE 4

Define strain, modulus of elasticity, Poisson's ratio and perform calculations.

STRAIN

When a force is applied to an object, the dimensions change. The change in length, relative to the original length, is called **linear or direct strain**. Linear strain is calculated using the equation:

$$\begin{aligned}\text{Direct Strain } (\epsilon) &= \frac{\text{change in length}}{\text{original length}} \\ &= \frac{\Delta l}{L}\end{aligned}$$

The units cancel each other out in the equation, so strain has no units of measure.

Shear strain refers to deformation of a body due to shear stress. It is measured in terms of the angle through which the deformation occurs.

Example 9

A column 10 m long is subjected to a load which causes its length to decrease 5 mm. What is the strain in the column?

Solution 9

From the equation, Direct strain $(\epsilon) = \frac{\Delta l}{L}$, the strain is:

$$\begin{aligned}\text{Direct Strain } (\epsilon) &= \frac{\Delta l}{L} \\ &= \frac{0.005 \text{ m}}{10 \text{ m}} \\ &= \mathbf{0.0005 \text{ (Ans.)}}\end{aligned}$$

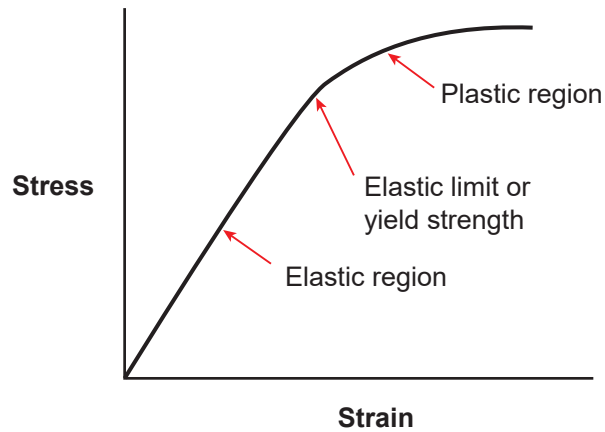
STRESS AND STRAIN

As the stress in a material increases, there is also an increase in strain. Hooke's Law states that, within the **elastic region**, the strain produced will be directly proportional to the stress that produces it (see Figure 14). There are limits under which Hooke's Law applies and these limits are distinct to the material being tested. Tests have shown that, as the level of stress increases, the material will pass through a number of stages of strain before it finally fails.

In the first stage, the stress causes the material to deform only while an external force continues to produce the stress. Once the force is removed, the material returns to its original shape. The strain caused in this stage or range is called **elastic strain**. In this region, the relationship between stress and strain follows Hooke's Law.



Figure 14 – Typical Stress vs Strain Curve



The maximum elastic strain that a material can handle is called the **elastic limit** or **yield strength** of the material, and any additional force above this limit will cause permanent deformation. Strain in this range is called **plastic strain**, and it will cause **plastic deformation** of the material. Once the material is strained into this **plastic region**, it will not return to its original shape even after the force causing the stress is removed. Once the material has moved into the plastic deformation range, its cross sectional area will be reduced. At this point, the stress will become concentrated and the material will quickly fail if more force is applied and the **ultimate stress** limit is exceeded. A material is considered to have completely failed once it reaches the ultimate stress limit.

FACTOR OF SAFETY

In engineering design it is standard to build in a safety margin to account for unexpected factors and variations. For loads, the factor of safety is the ratio of the elastic limit and the maximum expected working stress:

$$\text{Factor of safety} = \frac{\text{Elastic Limit}}{\text{Maximum Working Stress}} \text{ or } \frac{\text{Ultimate stress}}{\text{Maximum Working Stress}}$$

The maximum allowable working stress, and thus the factor of safety, depends on the following variables:

- Nature of the load (i.e. gradually applied, sudden impact, or repeated loading)
- Value of the maximum load
- Reliability of the material selected
- Uniformity of the material in question
- Severity of the consequences of failure
- Accuracy of the test data

MODULUS OF ELASTICITY

In the elastic region, the ratio of stress vs. strain is a specific constant for each individual material and tests have determined this constant for various materials. This ratio is called the **Modulus of Elasticity** or **Young's Modulus** and it is used as a measure of stiffness for materials.

$$\begin{aligned}\text{Modulus of elasticity } E &= \frac{\text{direct stress}}{\text{direct strain}} \\ &= \frac{P/A}{\Delta l/L} \\ &= \frac{PL}{A\Delta l}\end{aligned}$$

Since ϵ is a pure number without units, the units for E are the same as for stress, that is, Pascals. It is commonly measured in GPa (gigapascals or 10^9 pascals).

In general, the values of Young's Moduli are the same for tension and compression, although there are some exceptions.

For shear stresses, the Modulus of Elasticity is called the Modulus of Rigidity, G , and is defined as the ratio of shear stress to shear strain or:

$$\begin{aligned}\text{Modulus of rigidity } (G) &= \frac{\text{shear stress } (\tau)}{\text{shear strain } (\gamma)} \\ &= \frac{\tau}{\gamma}\end{aligned}$$

Some typical values for the modulus of elasticity and rigidity are compared in Table 2. Note that larger values indicate greater stiffness and less deformation for a given stress.

Table 2 – Typical Values for Modulus of Elasticity and Rigidity

Material	Modulus of Elasticity (GPa)	Modulus of Rigidity (Gpa)
Diamond	1000	
Tungsten carbide	450-650	
Low alloy steel	200-207	79
Stainless steel	190-200	73
Silicon	107	
Aluminum	69	26
Nylon	2-4	
Rubber	0.01-0.1	



Example 10

A steel bar with a diameter of 5 cm and a length of 3 m is subjected to a tensile load of 200 kN. If the elastic limit is 600 MPa and E is 200 GPa, calculate the stress and strain in the bar, the increase in its length and the factor of safety.

Solution 10

Area of the bar is

$$\begin{aligned} A &= \pi r^2 \\ &= \pi(0.025 \text{ m})^2 \\ &= 0.002 \text{ m}^2 \end{aligned}$$

Stress is:

$$\begin{aligned} \text{Direct stress} &= \frac{P}{A} \\ &= \frac{200 \text{ kN}}{0.002 \text{ m}^2} \\ &= \mathbf{100.0 \text{ MPa (Ans.)}} \end{aligned}$$

$$\begin{aligned} \text{Modulus of Elasticity (E)} &= \frac{\text{direct stress}}{\epsilon} \\ \epsilon &= \frac{\text{direct stress}}{E} \\ &= \frac{100 \text{ MPa}}{200 \text{ GPa}} \\ &= \frac{100 \times 10^6 \text{ Pa}}{200 \times 10^9 \text{ Pa}} \\ &= \mathbf{0.0005 \text{ (Ans.)}} \end{aligned}$$

Increase in length Direct strain (ϵ) = $\frac{\Delta l}{L}$ is :

$$\begin{aligned} \epsilon &= \frac{\Delta l}{L} \\ \Delta l &= \epsilon L \\ &= 0.0005 \times 3 \text{ m} \\ &= 0.0015 \text{ m} \\ &= \mathbf{1.50 \text{ mm (Ans.)}} \end{aligned}$$

Factor of safety: Factor of safety = $\frac{\text{Elastic limit}}{\text{Maximum working stress}}$ is:

$$\begin{aligned}\text{Factor of safety} &= \frac{\text{Elastic limit}}{\text{Maximum working stress}} \\ &= \frac{600 \text{ MPa}}{100.0 \text{ MPa}} \\ &= \mathbf{6.0 \text{ (Ans.)}}\end{aligned}$$

POISSON'S RATIO

When a bar is stretched, there is not only an increase in its axial length but also a corresponding decrease in its lateral width. A tensile stress acting in any direction on an object produces a tensile strain in this direction and also produces a compressive strain in every direction perpendicular to the first. Compressive stress on an object causes compressive strain in its own direction, and tensile strain in every lateral direction. The ratio between the lateral or perpendicular strain and the axial or longitudinal strain is called Poisson's ratio or μ (mu) and is defined as:

$$\text{Poisson's ratio } (\mu) = \frac{\text{lateral strain}}{\text{axial strain}}$$

For most metals, Poisson's ratio is between 0.25 and 0.35

Example 11

A 5 cm square steel bar with a length of 1.2 m is subjected to a tensile load of 285 kN. If E is 210 GPa and μ is 0.3, calculate the change in dimensions of the bar.

Solution 11

Area of the bar is:

$$\begin{aligned}A &= 5 \text{ cm} \times 5 \text{ cm} \\ &= 25 \text{ cm}^2 \\ &= 0.0025 \text{ m}^2\end{aligned}$$

Stress:

$$\begin{aligned}\text{Direct stress } \sigma &= \frac{P}{A} \text{ is:} \\ \text{Direct stress } \sigma &= \frac{P}{A} \\ &= \frac{285 \text{ kN}}{0.0025 \text{ m}^2} \\ &= 114\,000 \text{ kPa} \\ &= 114 \text{ MPa}\end{aligned}$$



Strain:

$$\text{Direct strain } (\epsilon) = \frac{\Delta l}{L} \text{ is:}$$

$$\begin{aligned} \text{Direct strain } (\epsilon) &= \frac{\sigma}{E} \\ &= \frac{114 \times 10^6 \text{ Pa}}{210 \times 10^9 \text{ Pa}} \\ &= 0.0005 \end{aligned}$$

Increase in length:

$$\begin{aligned} \text{Direct strain } (\epsilon) &= \frac{\Delta l}{L} \text{ is:} \\ \epsilon &= \frac{\Delta L}{L} = \frac{\text{change in length}}{\text{length}} \\ \Delta L &= \epsilon L \\ &= 0.0005 \times 1.2 \text{ m} \\ &= 0.0006 \text{ m} \\ &= 0.6 \text{ mm} \end{aligned}$$

Axial strain:

$$\begin{aligned} \text{Poisson's ratio } (\mu) &= \frac{\text{lateral strain}}{\text{axial strain}} \text{ is:} \\ \text{lateral strain} &= \text{axial strain} \times \mu \\ &= 0.0005 \times 0.3 \\ &= 0.00015 \end{aligned}$$

Decrease in width:

$$\begin{aligned} \text{Direct strain } (\epsilon) &= \frac{\Delta l}{L} \text{ is:} \\ \epsilon &= \frac{\Delta l}{L} = \frac{\text{change in length}}{\text{width}} \\ \Delta l &= \epsilon L \\ &= 0.00015 \times 5 \text{ cm} \\ &= 0.00075 \text{ cm} \end{aligned}$$



New dimensions of the bar are:

$$\begin{aligned}\text{New length} &= 1200 \text{ mm} + 0.6 \text{ mm} \\ &= \mathbf{1200.6 \text{ mm (Ans.)}}\end{aligned}$$

$$\begin{aligned}\text{New width} &= 5 \text{ cm} - 0.00075 \text{ cm} \\ &= 4.9992 \text{ cm} \\ &= \mathbf{49.992 \text{ mm (Ans.)}}\end{aligned}$$



OBJECTIVE 5

Define the thermal expansion of bars, including reactions, under conditions of restricted expansion and reactions of bars composed of dissimilar metals.

THERMAL EXPANSION

When metals are heated or cooled they expand or contract. The amount of expansion or contraction is dependent on the length of the material and the coefficient of thermal (also known as linear) expansion α for that particular material. The coefficient of linear expansion of a material is the longitudinal expansion for each unit of length for each degree of increase in temperature. The units are simply “per °C”. The coefficient is constant for a wide range of temperatures.

The strain due to thermal effects is determined by the equation:

$$\varepsilon = \alpha \times (T_2 - T_1)$$

For a bar of length L , the change in length will be:

$$\text{Change in length } (\Delta l) = L \alpha (T_2 - T_1)$$

$$L = \text{original length}$$

$$\alpha = \text{coefficient of linear expansion}$$

$$(T_2 - T_1) = \text{rise in temperature}$$

If an object is secured or fixed in a certain position, then its ability to move or expand is restricted or eliminated completely. If this object is then subjected to an increase or decrease in temperature, stresses will be developed in the material because its expansion or contraction is constrained. These **thermal stresses** are cumulative with any other stresses that the material may be subjected to when evaluating the material's ability to handle loads.

Example 12

A copper bar is 2.5 m long at 16°C. The coefficient of thermal expansion is 18×10^{-6} per °C and E is 110 GPa. If the temperature increases to 27°C, what is the thermal strain and increase in length if the bar's movement is not restricted? If the bar is fixed at both ends, what is the increase in the stress?

Solution 12

Thermal strain is found from:

$$\varepsilon = \alpha \times (T_2 - T_1):$$

$$\begin{aligned} \varepsilon &= \alpha \times (T_2 - T_1) \\ &= 18 \times 10^{-6} / ^\circ\text{C} \times (27 - 16)^\circ\text{C} \\ &= 0.0002 \text{ (Ans.)} \end{aligned}$$

Increase in length using equation:

$$\text{Direct strain } (\epsilon) = \frac{\Delta l}{L} \text{ is:}$$

$$\text{Direct strain } (\epsilon) = \frac{\Delta l}{L}$$

$$\begin{aligned} \Delta l &= \epsilon L \\ &= 0.0002 \times 2.5 \text{ m} \\ &= 0.0005 \text{ m} \\ &= 0.5 \text{ mm (Ans)} \end{aligned}$$

Stress, E is:

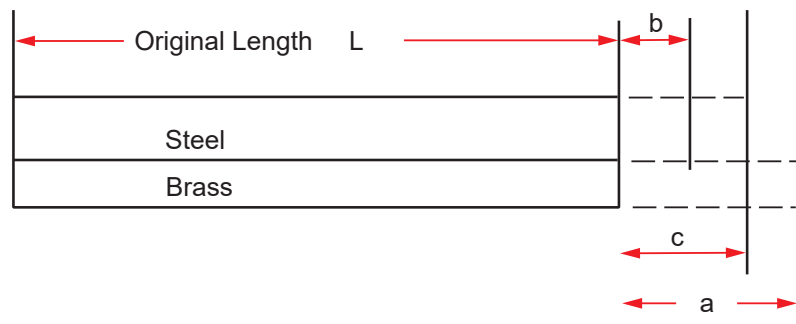
$$E = \frac{\text{direct stress}}{\text{direct strain}}$$

$$\begin{aligned} \text{direct stress} &= E \times \text{direct strain} \\ &= 110 \text{ GPa} \times 0.0002 \\ &= 0.022 \text{ GPa} \\ &= \mathbf{22.0 \text{ MPa (Ans.)}} \end{aligned}$$

THERMAL EXPANSION OF COMPOSITE BARS

A composite bar is one that is composed of different metals such as the one shown in Figure 15. Because brass has a higher coefficient of thermal expansion than steel, it is restricted by the steel and expands less than when it is heated on its own. Figure 15 shows that the brass expands only by length c instead of length a . The steel is forced by the brass to expand more than when it is heated on its own, that is, it expands to length c instead of length b .

Figure 15 – Composite Bar





The change in length in the brass bar, if unrestricted, is:

$$\text{Change in length } (\Delta l) = L \alpha (T_2 - T_1)$$

Let this value be represented by “a”:

$$a = L \alpha_b (T_2 - T_1)$$

Therefore:

$$\alpha_b = \frac{a}{L \times (T_2 - T_1)}$$

and the strain $\epsilon = \alpha \times \Delta T$ is:

$$\begin{aligned} \epsilon &= \alpha \times (T_2 - T_1) \\ \epsilon_b &= \alpha_b \times (T_2 - T_1) \\ &= \frac{a \times (T_2 - T_1)}{L \times (T_2 - T_1)} \\ &= \frac{a}{L} \end{aligned}$$

Normal change in length in the steel bar, if unrestricted, is:

$$\text{Change in length } (\Delta l) = L \alpha (T_2 - T_1)$$

Let this value be represented by “b”:

$$b = L \alpha_s (T_2 - T_1)$$

Therefore:

$$\alpha_s = \frac{b}{L \times (T_2 - T_1)}$$

and the strain $\epsilon = \alpha \times \Delta T$ is:

$$\begin{aligned} \epsilon &= \alpha \times (T_2 - T_1) \\ \epsilon_s &= \alpha_s \times (T_2 - T_1) \\ &= \frac{b \times (T_2 - T_1)}{L \times (T_2 - T_1)} \\ &= \frac{b}{L} \end{aligned}$$

Let “c” represent the actual expansion of the composite bar. The difference in expansion for the brass portion will be, $a - c$, which introduces a compressive stress in that portion of the bar. The difference in expansion for the steel portion, $c - b$, causes a tensile stress.

The difference in the free expansion, $a - b$, is derived by substituting for a and b in the following equation:

$$\begin{aligned} a - b &= [\alpha_b \times (T_2 - T_1) \times L] - [\alpha_s \times (T_2 - T_1) \times L] \\ \frac{a - b}{L} &= [\alpha_b \times (T_2 - T_1)] - [\alpha_s \times (T_2 - T_1)] \\ \frac{a - b}{L} &= \epsilon_b - \epsilon_s \end{aligned}$$

Note: ϵ_b has a negative value because the expansion of the brass is restricted.

Therefore, to determine the absolute value of $\frac{a - b}{L}$:

$$\begin{aligned} \frac{a - b}{L} &= -\epsilon_b - \epsilon_s \\ \frac{a - b}{L} &= \epsilon_b + \epsilon_s \end{aligned}$$

This gives the relationship:

Difference in free expansion per unit length = strain in brass + strain in steel

Strains can be written in terms of stress and modulus of elasticity, as follows:

$$\begin{aligned} \epsilon_b + \epsilon_s &= (\alpha_b - \alpha_s) \times (T_2 - T_1) \\ \frac{\sigma_b}{E_b} + \frac{\sigma_s}{E_s} &= (\alpha_b - \alpha_s) \times (T_2 - T_1) \end{aligned}$$

Because the force in each part of the bar must be equal, the stresses are related by the equation:

$$\begin{aligned} \sigma_s \times A_s &= \sigma_b \times A_b \\ \sigma_b &= \frac{\sigma_s \times A_s}{A_b} \end{aligned}$$

Substituting this in: $\sigma_b = \frac{\sigma_s \times A_s}{A_b}$ the stress in the steel bar is:

$$\begin{aligned} \frac{\sigma_s A_s}{E_b A_b} + \frac{\sigma_s}{E_s} &= (\alpha_b - \alpha_s) \times (T_2 - T_1) \\ \sigma_s &= \frac{(\alpha_b - \alpha_s) \times (T_2 - T_1)}{\frac{A_s}{E_b A_b} + \frac{1}{E_s}} \end{aligned}$$



Example 13

A steel bar with a cross-sectional area of 19 cm^2 is fastened securely to a brass bar with a cross-sectional area of 13 cm^2 . The temperature of the composite assembly is raised from 100°C to 156°C . Calculate the stress in each portion of the bar given that:

Coefficient of thermal expansion for steel = $12 \times 10^{-6} \text{ per } ^\circ\text{C}$

Coefficient of thermal expansion for brass = $20 \times 10^{-6} \text{ per } ^\circ\text{C}$

Modulus of elasticity for steel = 210 GPa

Modulus of elasticity for brass = 91 GPa

Solution 13

Stress in the steel portion $\sigma_s = \frac{(\alpha_b - \alpha_s) \times (T_2 - T_1)}{\frac{A_s}{E_b A_b} + \frac{1}{E_s}}$ is:

$$\begin{aligned}\sigma_s &= \frac{(\alpha_b - \alpha_s) \times (T_2 - T_1)}{\frac{A_s}{E_b A_b} + \frac{1}{E_s}} \\ &= \frac{(20 \times 10^{-6} / ^\circ\text{C} - 12 \times 10^{-6} / ^\circ\text{C}) \times (156^\circ\text{C} - 100^\circ\text{C})}{\frac{19 \text{ cm}^2}{91 \times 10^9 \text{ Pa} \times 13 \text{ cm}^2} + \frac{1}{210 \times 10^9 \text{ Pa}}} \\ &= \frac{8 \times 10^{-6} \times 56}{0.0161 \times 10^{-9} / \text{Pa} + 0.0048 \times 10^{-9} / \text{Pa}} \\ &= \frac{448 \times 10^3 \text{ Pa}}{0.0209} \\ &= \mathbf{21\,435 \text{ kPa (Ans.)}}\end{aligned}$$

Stress in the brass portion is from: $\sigma_b = \frac{\sigma_s \times A_s}{A_b}$:

$$\begin{aligned}\sigma_b &= \frac{\sigma_s \times A_s}{A_b} \\ &= \frac{21435 \text{ kPa} \times 19 \text{ cm}^2}{13 \text{ cm}^2} \\ &= \mathbf{31\,328 \text{ kPa (Ans.)}}\end{aligned}$$

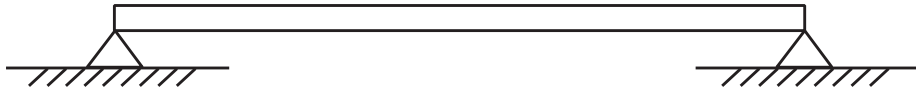
OBJECTIVE 6

Define and calculate shear forces and bending moments for simply supported beams and cantilevers.

LOADS ON BEAMS

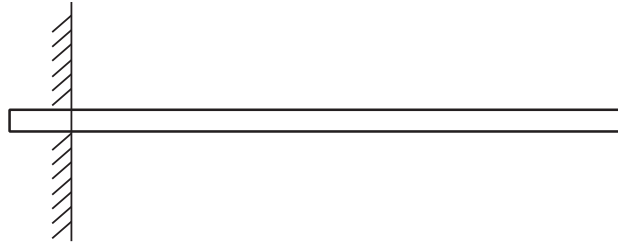
A beam is a structural member designed primarily to support loads that are perpendicular to the longitudinal axis of the beam. Types of beams are distinguished by the method which they are supported. Simply supported beams, (Figure 16), have a single support at each end of the beam.

Figure 16 – Simple Supported Beam



Cantilever beams (Figure 17.) are secured or fixed firmly at one end only.

Figure 17 – Cantilever Beam



There are two types of loads that will be evaluated in this section of the module:

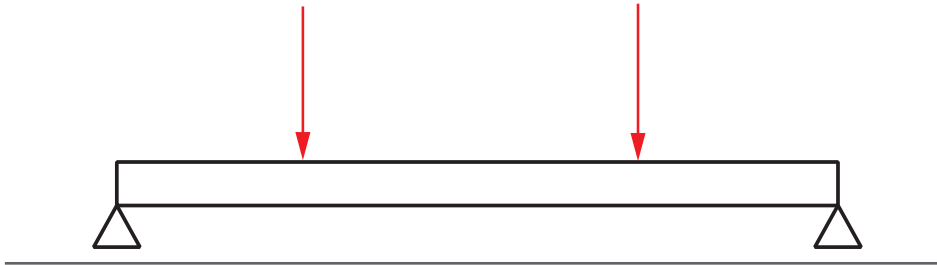
- Concentrated
- Uniformly distributed



Concentrated Loads

Concentrated loads (Figure 18) are loads that are concentrated at a single point or location on the beam.

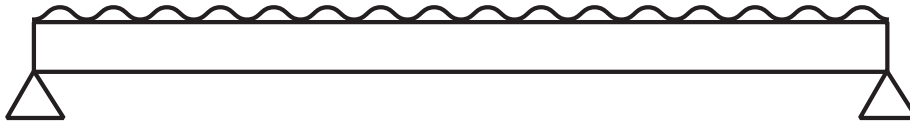
Figure 18 – Beam with Concentrated Loads



Uniformly Distributed Loads

Uniformly distributed loads (Figure 19) are spread uniformly across a section of the beam or the entire length.

Figure 19 – Beam with Uniformly Distributed Load



The loads on a beam will result in both of the following:

- Shear forces
- Bending moments

SHEAR FORCES

Shear forces tend to cause the beam to shear in a vertical direction. If the direction is the one shown in Figure 20(a) or in a clockwise direction relative to the applied forces, it is called **positive shear**. If the direction is the one shown in Figure 20(b) or in an anticlockwise direction relative to the applied forces, it is **negative shear**.

Figure 20 – Shear Forces

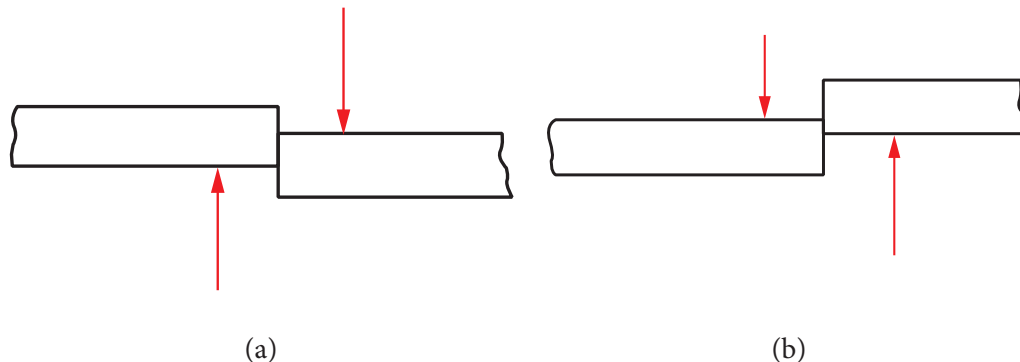
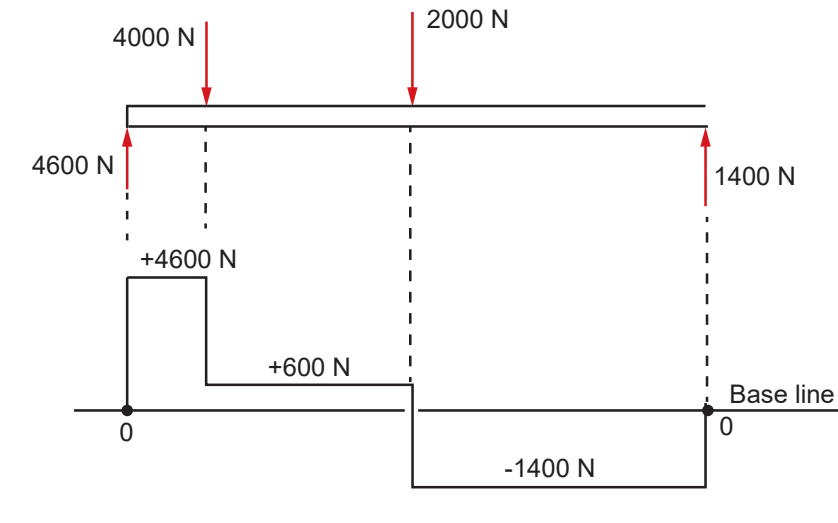


Figure 21 illustrates the change in shear forces across a simply supported beam with two point loads. Reviewing the shear forces on the beam and starting on the left hand side, the shear force is 4600 N and is positive until it reaches the 4000 N load. Because the 4000 N load acts in the opposite direction, the shear force is reduced to 600 N but is still positive. At the next load of 2000 N, the shear force is again reduced to -1400 N and is now negative. The shear force remains at -1400 N between the 2000 N load and the right hand side of the beam, where it is restored to zero shear force by the 1400 N force at the support. Diagrams such as the one shown in Figure 21 are the clearest way to show the shear forces.

Figure 21 – Shear Forces on a Simple Beam

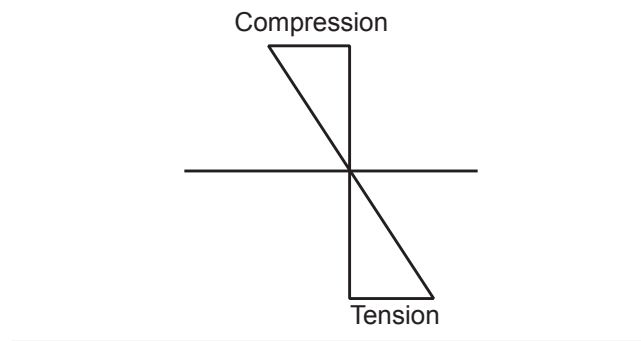


BENDING MOMENTS

Bending force is caused by moments created on the beam by applied forces. The use of moments to determine forces was covered in Objective 1. In static equilibrium, clockwise moments must equal anticlockwise moments and vertical forces must equal the downward forces.

The stress profile produced by a bending force is shown in Figure 22. If the forces cause the beam to deflect downward, the top surface of the beam experiences compression and the bottom of the beam experiences tension. The bending moment is positive when the moments move in a counter-clockwise direction. Bending moments are negative when moving in a clockwise direction.

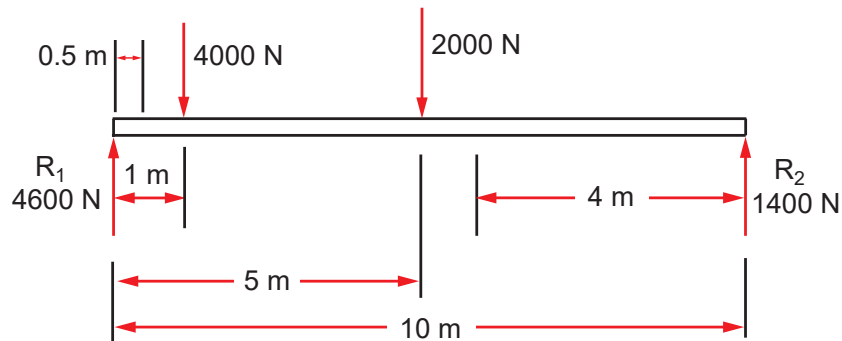
Figure 22 – Stress Profile due to Bending Forces





To evaluate the bending moments, use the dimensions between the forces, as shown in Figure 23.

Figure 23 – Dimensions for a Simple Beam



The resultant bending moments are shown in Figure 24. At the point 0.5 m from the left hand side, either the forces to the left or to the right side of this point can be used because they are equal for equilibrium. Since there is only one force on the left side of the beam, it is easier to calculate:

$$\begin{aligned}\text{Bending moment at 0.5 m from } R_1 &= 4600 \text{ N} \times 0.5 \text{ m} \\ &= 2300 \text{ Nm}\end{aligned}$$

The remaining moments are:

$$\begin{aligned}\text{Bending moment at 1 m from } R_1 &= 4600 \text{ N} \times 1 \text{ m} \\ &= 4600 \text{ Nm}\end{aligned}$$

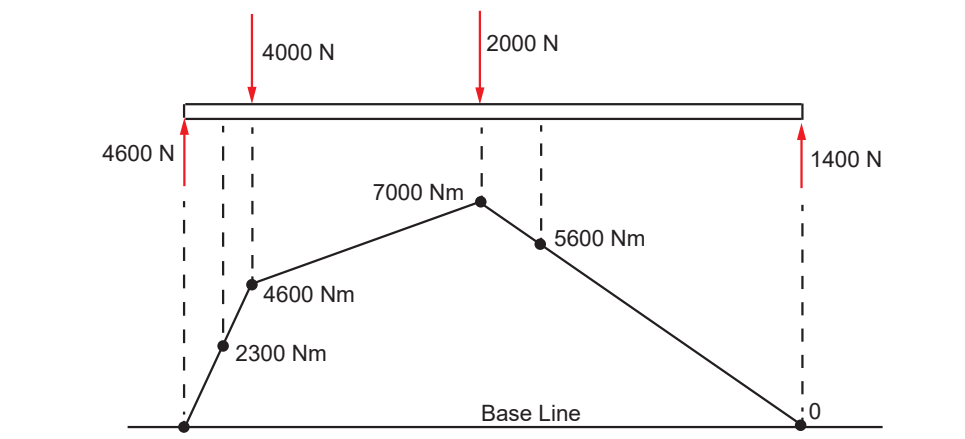
$$\begin{aligned}\text{Bending moment at 5 m from } R_1 &= (4600 \text{ N} \times 5 \text{ m}) - (4000 \text{ N} \times 4 \text{ m}) \\ &= 7000 \text{ Nm}\end{aligned}$$

$$\begin{aligned}\text{Bending moment at 6 m from } R_1 &= (4600 \text{ N} \times 6 \text{ m}) - (4000 \text{ N} \times 5 \text{ m}) - (2000 \text{ N} \times 1 \text{ m}) \\ &= 5600 \text{ Nm}\end{aligned}$$

To check the results, take the moments to the right of the point 4 m from R_2 :

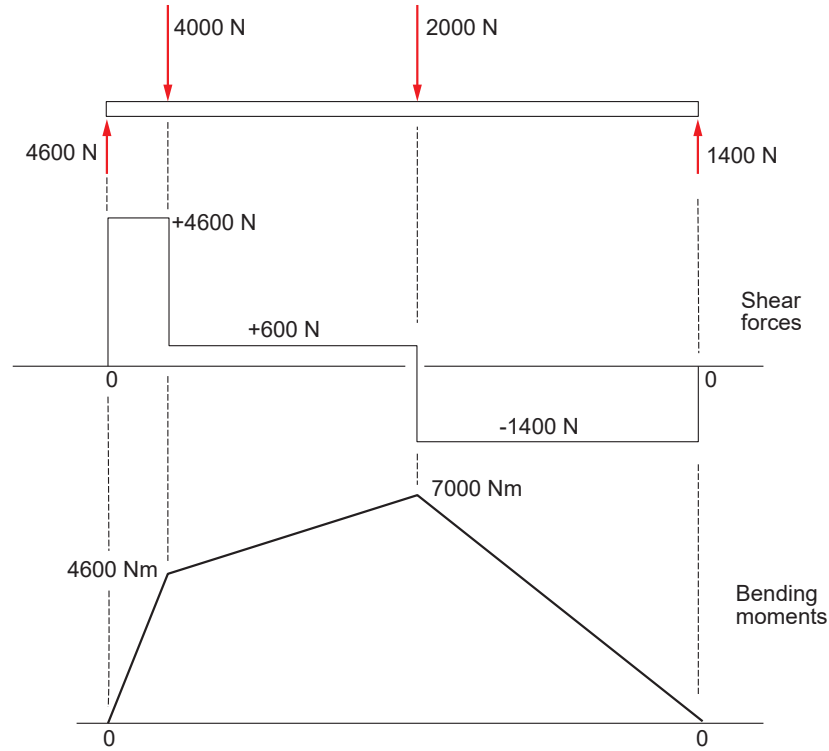
$$\begin{aligned}\text{Bending moment at 4 m from } R_2 &= 1400 \text{ N} \times 4 \text{ m} \\ &= 5600 \text{ Nm}\end{aligned}$$

Figure 24 – Bending Moments on a Simple Beam



It is common to show both the shear forces and the bending moments on the same diagram, as shown in Figure 25. Note that the maximum bending moment occurs at the same location where the shear force crosses the axis and is zero.

Figure 25 – Combined Shear Force & Bending Moment Diagram

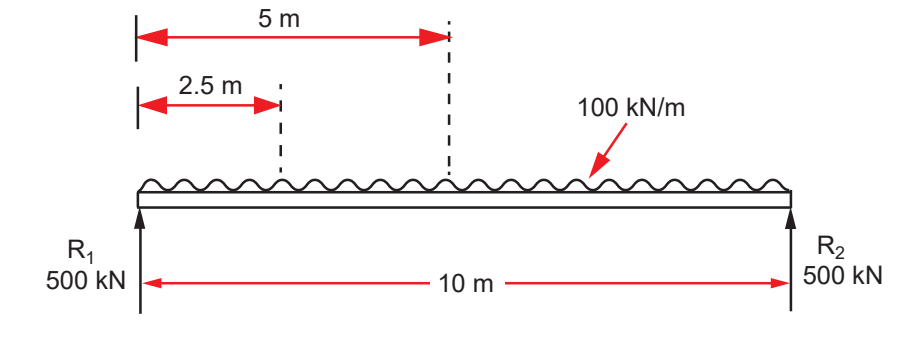


Example 14

A simply supported beam carries a distributed load of 100 kN/m, as shown in Figure 26. Show the shear forces and bending moments on a diagram and determine the location of the maximum shear force and bending moment.

Solution 14

Figure 26 – Simply Supported Beam (Example 14)





The total load on the beam is $100 \text{ kN/m} \times 10 \text{ m} = 1000 \text{ kN}$. For the beam to be in equilibrium, each reaction must carry half the load, 500 kN . Therefore, the shear force at the left end (at R_1) is 500 kN to counter the force of the support. At 1 m from the left end, the shear force becomes $500 \text{ kN} - 100 \text{ kN} = 400 \text{ kN}$. At the midpoint of the beam, the shear force is zero and then becomes negative, as shown in Figure 27. Therefore, the maximum shear force is 500 kN and occurs at both ends of the beam.

Because the shear force is zero at the mid-point of the beam, this is also the point of maximum bending moment. To find the bending moment at the mid-point, take the moments to the left of the mid-point of the beam and assume that the distributed load is concentrated at the midpoint:

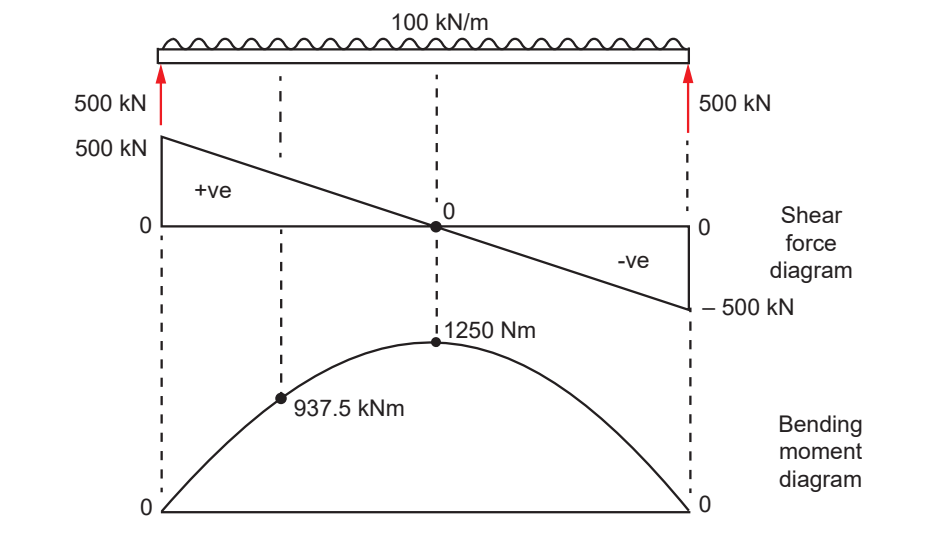
$$\begin{aligned} \text{Bending moment at the mid-point} &= (500 \text{ kN} \times 5 \text{ m}) - (100 \text{ kN/m} \times 5 \text{ m} \times 2.5 \text{ m}) \\ &= 2500 \text{ kNm} - 1250 \text{ kNm} \\ &= \mathbf{1250 \text{ kNm (Ans.)}} \end{aligned}$$

Similarly, to find the BM at other points between the mid-point and the left end, calculate the moment to the left of those other points. For example, at 2.5 m from the left end, the BM can be calculated as follows:

$$\begin{aligned} \text{Bending moment at } 2.5 \text{ m from } R_1 &= (500 \text{ kN} \times 2.5 \text{ m}) - (100 \text{ kN/m} \times 2.5 \text{ m} \times 1.25 \text{ m}) \\ &= 1250 \text{ kNm} - 312.5 \text{ kNm} \\ &= 937.5 \text{ kNm} \end{aligned}$$

If the bending moments for more points are calculated along the beam, the bending moment diagram forms a parabolic curve (Figure 27), which is characteristic of a distributed load.

Figure 27 – Shear Force and Bending Moment Diagrams for Example 14



Example 15

A cantilever beam is subjected to two forces, one of 500 kN at a distance of 4 m from the fixed end and the other 200 kN, a distance of 8 m from the fixed end. Sketch the shear force and bending moment diagrams.

Solution 15

Referring to Figure 28, the shear force at the fixed end is found by adding the forces applied to the right side which equal 700 kN. Shear force drops to 200 kN at the location of the 500 kN force.

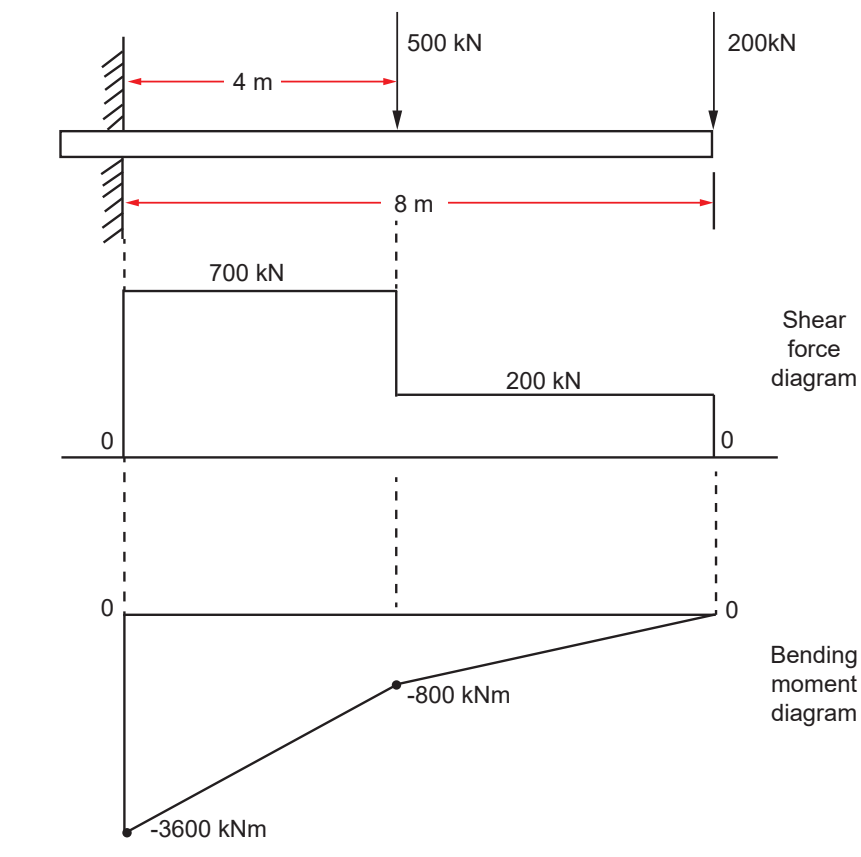
Referring to Figure 28, the bending moment at the fixed end is derived by taking the moments to the right of that point:

$$\begin{aligned}\text{Bending moment at the fixed end} &= - [(500 \text{ kN} \times 4 \text{ m}) + (200 \text{ kN} \times 8 \text{ m})] \\ &= -(2000 \text{ kNm} + 1600 \text{ kNm}) \\ &= -3600 \text{ kNm (Ans.)}\end{aligned}$$

$$\begin{aligned}\text{Bending moment at 500 kN load} &= -(200 \text{ kN} \times 4 \text{ m}) \\ &= -800 \text{ kNm (Ans.)}\end{aligned}$$

Note that the moment is considered to be negative because it is clockwise in direction.

Figure 28 – Shear Force and Bending Moment Diagrams for Example 15





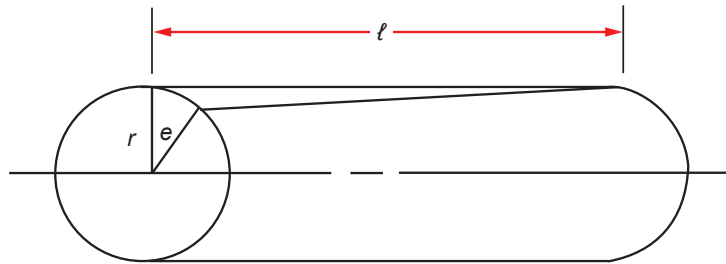
OBJECTIVE 7

Perform calculations involving the fundamental torsion equation and explain the relationship between torque and stress.

TORSION

When a shaft is used to transmit power in a machine, it is subjected to a rotational force known as twisting moment or torque that tends to twist or turn the shaft. Torque causes a shear force in the shaft. A deflection of the layers of metal which make up the shaft occurs with twisting in the shaft (Figure 29) and this deflection is called torsion. Shear forces are related to the angle of twist to determine the torque applied and to derive the power transmitted. The amount of shear force or torsion can be calculated by knowing the angle of twist at the shaft face in radians (θ) and the radius from the centre to the outside surface of the shaft. This principle is the basis for torquemeters that measure the power output of rotating equipment.

Figure 29 – Shaft Torsion



The fundamental torsion equation is used to determine the shear stress at any point on the radius. Maximum stress exists at the outer periphery of the shaft. This equation applies to circular shafts only.

$$\tau = \frac{Tr}{J}$$

Where

τ = shear stress, pascals

T = twisting moment or torque, Nm

J = polar second moment of area of cross-section about shaft, m^4

r = radius of shaft, m

G = modulus of rigidity, pascals

θ = angle of twist, radians

Shear stress can be expressed in terms of shear strain and the modulus of rigidity as per $G = \frac{\tau}{\gamma}$
 Shear strain can also be calculated from the angle of twist (measured in radians) by the relationship:

$$\gamma = \frac{r\theta}{l}$$

so that the torsion equation becomes:

$$\tau = \frac{Tr}{J}$$

but, $\tau = G\gamma$

$$\tau = \frac{Tr}{J} = G\gamma$$

also, $\frac{T}{J} = \frac{\delta}{r} = \frac{G\theta}{l}$

$$\frac{Tr}{J} = \frac{Gr\theta}{l}$$

Torque can then be determined by the equation:

$$T = \frac{G\theta J}{l}$$

Another calculation that is important when dealing with torsion is that of the **polar second moment** of a shaft. When a number of different areas are multiplied by the squares of their distances from a common point of reference, then the sum of the resulting products is called the **second moment** of the total area.

The second moment of a shaft, taken from its polar centre, is thus called the polar second moment of the shaft, and it is referred to mathematically as J.

The polar second moment for a solid shaft is:

$$J = \frac{\pi}{2} r^4$$

or

$$J = \frac{\pi d^4}{32}$$

and for a hollow shaft:

$$J = \frac{\pi}{2} (r_1^4 - r_2^4)$$

or

$$J = \frac{\pi}{32} (d_1^4 - d_2^4)$$



Example 16

A rotating solid shaft of 200 mm diameter twists 0.75° over a length of 4 m. If the modulus of rigidity is 100 GPa, calculate the torque transmitted and the maximum shear stress.

Solution 16

Twist in radians is determined by the fact that there are 2π radians in a circle so that:

$$\begin{aligned}\theta &= \frac{0.75}{360} \times 2\pi \text{ radians} \\ &= 0.0131 \text{ radians}\end{aligned}$$

Polar second moment is found using the equation $J = \frac{\pi d^4}{32}$:

$$\begin{aligned}J &= \frac{\pi d^4}{32} \\ &= \frac{\pi \times (0.2)^4}{32} \\ &= 0.000157 \text{ m}^4\end{aligned}$$

Find the torque, using the equation: $T = \frac{G\theta J}{l}$:

$$\begin{aligned}T &= \frac{G\theta J}{l} \\ &= \frac{100 \times 10^9 \text{ N/m}^2 \times 0.0131 \times 0.000157 \text{ m}^4}{4 \text{ m}} \\ &= 25 \times 10^9 \times 0.0131 \times 0.000157 \text{ Nm} \\ &= 51417.5 \text{ Nm} \\ &= \mathbf{51.4 \text{ kNm (Ans.)}}\end{aligned}$$

Find the stress, using the torsion equation:

$$\begin{aligned}\tau &= \frac{Tr}{J} \\ &= \frac{51.4 \text{ kNm} \times 0.1 \text{ m}}{0.000157 \text{ m}^4} \\ &= 32\,740 \text{ kN/m}^2 \\ &= \mathbf{32.74 \text{ MPa (Ans.)}}\end{aligned}$$

OBJECTIVE 8

Explain the relationship between torque and power, and calculate maximum and mean torque for solid shafts of circular cross section.

TORQUE AND POWER

In the module on Angular Motion (PE2-1-9), the relationship between torque (T in Nm), speed (n in rev/min) and power (P in watts) was established as:

$$P = 2\pi T \frac{n}{60}$$

Another form of this equation can be used which uses ω (angular velocity in rad/s)

$$P = T\omega$$

MAXIMUM AND MEAN TORQUE

When using torque to calculate shaft stress and power, it is important to understand whether the torque varies with rotation. In turbines, the torque is constant through each revolution of the shaft. However, in reciprocating engines, the torque varies depending on which part of the cycle the engine is in and whether the engine operates on the Otto or Diesel cycle. In this case, there is a mean torque which applies to the calculation of power. A maximum torque determines the maximum stress on the shaft. It is usually expressed as a ratio of maximum to mean torque.

Example 17

A reciprocating engine runs at 200 rpm and drives a 400 mm diameter solid shaft. Maximum allowable stress is 50 MPa and ratio of maximum to mean torque is 1.5. What is the maximum power that can be transmitted?

Solution 17

Polar inertia is found using the equation $J = \frac{\pi r^4}{2}$:

$$\begin{aligned} J &= \frac{\pi r^4}{2} \\ &= \frac{\pi \times 0.2^4}{2} \\ &= 0.0025 \text{ m}^4 \end{aligned}$$



Torque is then obtained from the equation $\tau = \frac{Tr}{J}$:

$$\begin{aligned}\tau &= \frac{Tr}{J} \\ T &= \frac{\tau J}{r} \\ &= \frac{50 \times 10^6 \text{ N/m}^2 \times 0.0025 \text{ m}^4}{0.2 \text{ m}} \\ &= 625\,000 \text{ Nm} \\ &= 625.0 \text{ kNm}\end{aligned}$$

Since this is the maximum torque, the mean torque is:

$$\begin{aligned}\text{mean torque} &= \frac{\text{maximum torque}}{1.5} \\ &= \frac{625.0}{1.5} \\ &= 416.67 \text{ kNm}\end{aligned}$$

From equation: $P = 2\pi T \frac{n}{60}$, the maximum power is:

$$\begin{aligned}P &= 2\pi T \frac{n}{60}, \\ &= 2\pi \times 416.67 \times \frac{200}{60} \\ &= \mathbf{8726.72 \text{ kW (Ans.)}}\end{aligned}$$

OBJECTIVE 9

Calculate stress in coupling bolts due to torque.

COUPLINGS

Bolted couplings are often used to connect shafts. Both the shaft and the bolts must be able to transmit the torque. If the radius at which the bolts are installed is known, the force applied to the bolts can be calculated. Given maximum allowable stress and the total sectional area of the bolt material, the required cross-sectional area and diameter of the bolts can be determined. If the bolt diameter and properties are known, it is possible to calculate the maximum torque allowed.

Example 18

Two 400 mm solid shafts are connected by a coupling which has 6 bolts on a 750 mm diameter circle. If the maximum allowable stress of the bolt material and the shaft is 50 MPa, what is the minimum diameter for each bolt?

Solution 18

Polar inertia is found using the equation: $J = \frac{\pi r^4}{2}$

$$\begin{aligned} J &= \frac{\pi r^4}{2} \\ &= \frac{\pi \times 0.2^4}{2} \\ &= 0.0025 \text{ m}^4 \end{aligned}$$

Torque is then obtained from the equation: $\tau = \frac{Tr}{J}$

$$\begin{aligned} \tau &= \frac{Tr}{J} \\ T &= \frac{\tau J}{r} \\ &= \frac{50 \times 10^6 \text{ N/m}^2 \times 0.0025 \text{ m}^4}{0.2 \text{ m}} \\ &= 625\,000 \text{ Nm} \\ &= 625.0 \times 10^3 \text{ Nm} \end{aligned}$$

Force applied to the bolts is found by dividing the torque by the radius of the bolt circle:

$$\begin{aligned} \text{Force} &= \frac{\text{torque}}{\text{radius}} \\ &= \frac{625.0 \times 10^3 \text{ Nm}}{0.375 \text{ m}} \\ &= 1666.67 \times 10^3 \text{ N} \end{aligned}$$



Since: Force = stress $\times$ area, the total area required is:

$$\begin{aligned}\text{area} &= \frac{\text{Force}}{\text{stress}} \\ A &= \frac{1666.67 \times 10^3 \text{ N}}{50 \times 10^6 \text{ N/m}^2} \\ &= 0.0333 \text{ m}^2\end{aligned}$$

Thus, minimum area of each bolt will be:

$$\begin{aligned}A &= \frac{0.0333 \text{ m}^2}{6} \\ &= 0.0056 \text{ m}^2\end{aligned}$$

Minimum radius of each bolt should be:

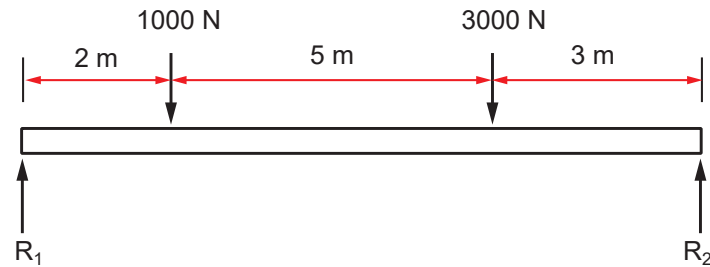
$$\begin{aligned}A &= \pi r^2 \\ r^2 &= \frac{A}{\pi} \\ &= \sqrt{\frac{0.0056 \text{ m}^2}{3.1416}} \\ &= \sqrt{0.0018} \\ &= 0.0422 \text{ m}\end{aligned}$$

Therefore, the minimum diameter of each bolt should be:

$$0.0844 \text{ m} \text{ or } \mathbf{84.4 \text{ mm (Ans.)}}$$

CHAPTER QUESTIONS

1. A simply supported beam is loaded as shown in Figure 30. What supporting forces are required at R_1 and R_2 to maintain the beam in equilibrium?



2. Define a centroid. Define the first moment of area and explain how it relates to the location of a centroid.
3. A circular column with a diameter of 40 cm carries a compressive load of 200 kN. What is the stress on the column?
4. A steel bar with a diameter of 6 cm and a length of 5 m is subjected to a tensile load of 250 kN. If the factor of safety is 5.8 and E is 225 GPa, calculate the following:
 - a) Stress
 - b) Strain
 - c) Increase in length
 - d) Elastic limit
5.
 - a) Calculate the safe load in kN that can be carried by a stud of 645.16 mm² cross-sectional area allowing a safe working stress of 30 MN/m².
 - b) Calculate the number of studs required to hold the cylinder cover of a diesel engine where the maximum pressure in the cylinder is 4.5 MPa and the diameter of the cover is 400 mm.



6. A steel bar is covered by a copper sheath over its entire length. This sheath is firmly affixed to the bar so that one cannot expand more than the other. Cross-sectional area of the steel bar is twice the cross-sectional area of the copper sheath. If there is zero stress in the bar, then its temperature is increased by 150°C , what now are the stresses in the steel and the copper?

Coefficient of linear expansion for the steel = $12 \times 10^{-6}/^{\circ}\text{C}$

Coefficient of linear expansion for the copper = $17 \times 10^{-6}/^{\circ}\text{C}$

E for steel = 210 GN/m^2

E for copper = 100 GN/m^2

7. A cantilever beam, 10 m long carries two concentrated loads, one at the free end and the other at the midpoint of the beam. The bending moments at the wall is 100 kNm and at the midpoint of the beam it is 30 kNm. Calculate the magnitudes of both loads.
8. A 406 mm diameter solid steel shaft in a reciprocating engine develops 7150 kW. The maximum stress allowed is 60 MN/m^2 and the maximum to mean torque ratio is 1.75:1. Calculate the rpm of the engine.
9. Two 450 mm solid shafts are connected by a coupling, which has a bolt circle of 900 mm diameter. Maximum allowable stress of the bolt material and shaft is 50 MPa. If the diameter of each bolt is 90 mm, calculate the number of bolts required.





CHAPTER 12

Fluid Mechanics

LEARNING OUTCOME

When you complete this chapter you should be able to:

Perform calculations related to fluid flows and pressure.

LEARNING OBJECTIVES

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

1. *Describe the basics of fluid mechanics.*
2. *Perform calculations related to pressure in a fluid, including center of pressure.*
3. *Explain buoyancy and perform calculations involving buoyancy principles.*
4. *Define and calculate thermal expansion of a vessel and its liquid contents.*
5. *Describe flow in open channels and calculate fluid flow through a weir.*
6. *Describe liquid flow in a pipe using the continuity equation.*
7. *Apply the law of conservation of energy to fluid flow and define Bernoulli's equation.*
8. *Calculate fluid flow from a vessel orifice.*
9. *Calculate flow using a venturi meter.*



OBJECTIVE 1

Describe the basics of fluid mechanics.

FLUID MECHANICS

Fluid mechanics is the study of the behaviour of fluids, either liquids or gases. The study of fluids at rest is called fluid statics, and the study of fluids in motion is called fluid dynamics.

Liquids are generally incompressible, and therefore, take the same shape as the container, possibly with a free surface if the volume of the fluid is less than that of the container.

Gases are compressible and will usually fill the container that they are in. Since liquids turn into gases, under certain pressure and temperature conditions, fluids may change from one to the other and containers may contain a combination of liquid and gas.

PROPERTIES OF FLUIDS

There are several basic properties of fluids that are used to perform calculations of fluid behaviour:

- Density
- Relative density
- Specific weight
- Viscosity

Density

Density (ρ , the Greek symbol rho) is the amount of mass (m) per unit volume (V) of a fluid.

Equation for density is:

$$\text{Density} = \frac{\text{mass}}{\text{volume}} \quad \text{or}$$

$$\rho \text{ (kg/m}^3\text{)} = \frac{m \text{ (kg)}}{V \text{ (m}^3\text{)}}$$

Because liquids are incompressible, the volume remains the same except for small changes due to pressure and temperature. Density remains essentially the same at all times. It is standard in the oil and gas industry to define liquid density at atmospheric pressure (101.325 kPa) and 15°C. Although other standards exist, there is little practical difference.

Since gases expand to fill the volume of the container, the density changes depending on the situation. Therefore, it is necessary to define the density of a gas based on a standard set of pressure and temperature conditions. The most common standard is 15°C and atmospheric pressure. For flow calculations, volume is expressed in terms of standard cubic meters (a cubic meter of fluid at standard conditions of 15°C and 101.325 kPa).

Relative Density

Instead of using actual densities, it is convenient to express density as a relative density, as compared to that of water. The relative density (RD) of a fluid is the ratio of its density (ρ) to the density of water at 15°C and 101.325 kPa. The density of water is 1000 kg/m³.

Equation for relative density is:

$$RD = \frac{\rho}{1000 \text{ kg/m}^3}$$

Some common relative densities are provided in Table 1.

Table 1 – Common Densities and Relative Densities		
Type of Fluid	Density kg/m ³	Relative Density
Water, at 0°C	1000	1.0
Water, at 100°C	958	0.958
Lubricating oil (average)	900	0.9
Mercury	13 540	13.54
Gasoline	680	0.68
Medium fuel oil	852	0.852
Heavy fuel oil	906	0.906
Air, at –40°C	1.514	0.001514
Air, at 0°C	1.292	0.001292
Air, at 120°C	0.8978	0.0008978
Aluminum	2700	2.7



Example 1

A tank with a volume of 5 m³ is filled with oil which has a relative density of 0.89. What is the mass of the oil?

Solution 1

Using equation: $RD = \frac{\rho}{1000}$, the density of the oil is:

$$RD = \frac{\rho}{1000 \text{ kg/m}^3}$$

$$\rho = RD \times 1000 \text{ kg/m}^3$$

$$= 0.89 \times 1000 \text{ kg/m}^3$$

$$= 890 \text{ kg/m}^3$$

Therefore, using equation: $\rho \text{ (kg/m}^3\text{)} = \frac{m(\text{kg})}{V(\text{m}^3)}$ the mass of the oil is:

$$\rho \text{ (kg/m}^3\text{)} = \frac{m(\text{kg})}{V(\text{m}^3)}$$

$$m = \text{kg/m}^3 \times V \text{ m}^3$$

$$= 890 \text{ kg/m}^3 \times 5 \text{ m}^3$$

$$= \mathbf{4450 \text{ kg (Ans.)}}$$

Specific Weight

Specific weight is the weight (w) of a fluid per unit volume. Weight is related to mass by means of Newton's second law ($w = mg$) with units in N (newtons). The formula for specific weight, denoted by the Greek symbol γ (gamma), is:

$$\gamma(\text{kN/m}^3) = \frac{w}{V}$$

The specific weight of water is 9.81 kN/m³. This value can be used to calculate the specific weight for any fluid (in kN/m³) if its relative density (RD) is known by the equation:

$$\gamma = 9.81(\text{kN/m}^3) \times RD$$

Some common specific weights are provided in Table 2.

Table 2 – Specific Weights	
Type of Fluid	Specific Weight γ , kN/m ³
Ethyl Alcohol	7.74
Gasoline	6.67
Glycerin	12.40
Mercury	133.00
Water, at 15°C	9.80

Viscosity

Viscosity expresses the reluctance to flow by a fluid acted upon by an external force. The coefficient of absolute viscosity of a fluid is a measure of its resistance to internal deformation or shear.

Measurement of absolute viscosity is carried out experimentally, the basic principle being that if a film of liquid, such as mineral oil, is placed between two parallel planes with the bottom one held stationary and the top one of known area moved at constant velocity, then the force required to maintain this velocity will depend upon the resistance to shear of the particular fluid being tested.

Molasses is a highly viscous fluid; water is much less viscous. The viscosity of a gas is small compared to that of water.

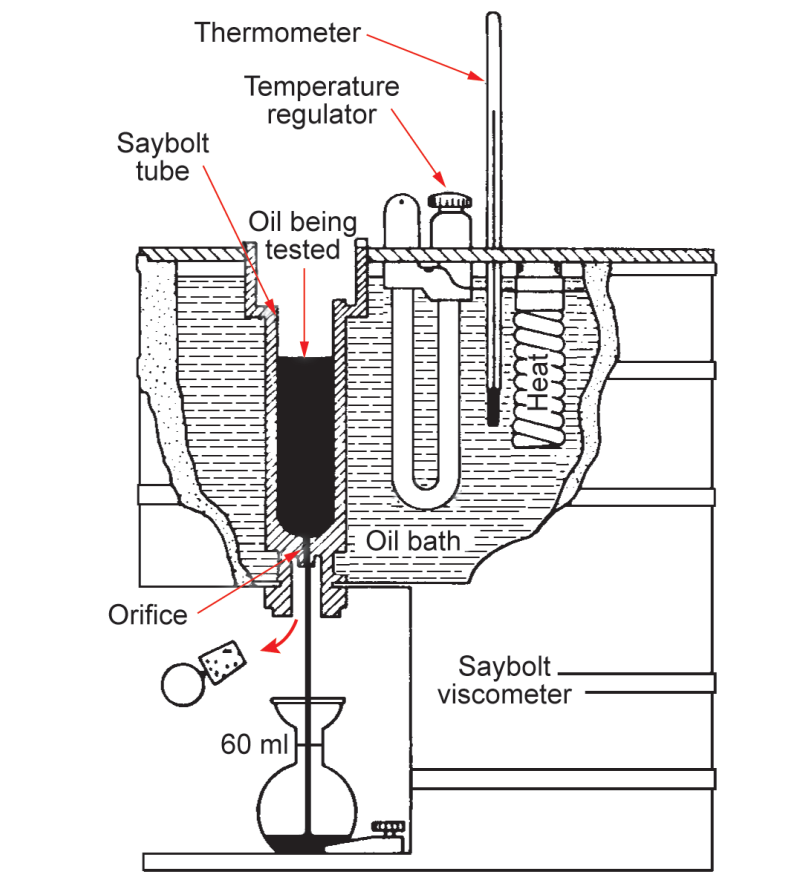
The unit of dynamic viscosity in the SI system is the pascal second (Pa·s) or millipascal second (m Pa·s)

Kinematic viscosity is the ratio of the absolute viscosity to the mass density. In the SI system the unit of kinematic viscosity is the square metre per second (m^2/s) or square millimetre per second (mm^2/s).

The measurement of the absolute viscosity of fluids (especially gases and vapours) requires elaborate equipment and considerable experimental skill. On the other hand, a rather simple instrument can be used for measuring the kinematic viscosity of oils and other viscous liquids.

The instrument adopted as a standard in this country is the Saybolt Universal Viscosimeter, shown in Figure 1. In measuring kinematic viscosity with this instrument, the time required for a small volume of liquid to flow through an orifice is determined; consequently the “Saybolt viscosity” of the liquid is given in seconds. For very viscous liquids, the Saybolt Furol instrument is used.

Figure 1 – Saybolt Viscosimeter





OBJECTIVE 2

Perform calculations related to pressure in a fluid, including center of pressure.

DEFINITION OF PRESSURE

Pressure (p) is defined as the force (F) applied by a fluid on a unit area (A). This can be stated by the equation (units are N/m^2 or Pa):

$$p = \frac{F}{A}$$

Example 2

A hydraulic piston with a diameter of 10 cm is required to exert a force of 2000 N. What does the pressure need to be in the hydraulic fluid?

Solution 2

Cross-sectional area of the piston is:

$$\begin{aligned} A &= \pi r^2 \\ &= \pi(0.05 \text{ m})^2 \\ &= 0.00785 \text{ m}^2 \end{aligned}$$

From equation: $p = \frac{F}{A}$, the pressure is:

$$\begin{aligned} p &= \frac{F}{A} \\ &= \frac{2000 \text{ N}}{0.00785 \text{ m}^2} \\ &= 254.8 \text{ kPa (Ans.)} \end{aligned}$$

PRESSURE IN A FLUID

Two principles describing pressure in fluids, also known as Pascal's laws, are as follows:

1. Pressure acts in all directions in a fluid
2. Where a fluid meets a solid surface, the pressure acts perpendicular to the surface

Since liquids are denser than gases, changes in elevation have a greater effect on pressure in liquids than pressure in gases. The pressure of a liquid at a specific elevation is determined by the height of the fluid above it.

This is expressed by the equation:

$$p = hw$$

The elevation (h) is in meters. The specific weight (w) of the liquid is obtained from Newton's second law, or from the equation:

$$w = \rho g$$

For water, this means that:

$$\begin{aligned} &= 1000 \text{ kg/m}^3 \times 9.81 \text{ N/kg} \\ &= 9.81 \text{ kN/m}^3 \end{aligned}$$

Therefore, the equation can also be written as:

$$p = h\rho g$$

Note: Pressure (p) is the difference in pressure between two elevations. If the pressure at the top of a fluid column is higher (or lower) than atmospheric, take the fluid column pressure into account.

Example 3

What is the pressure exerted on a submarine at a depth of 200 m if the relative density of seawater is 1.03?

Solution 3

$$\begin{aligned} \text{RD} &= \frac{\rho}{1000 \text{ kg/m}^3} \\ \rho &= 1000 \text{ kg/m}^3 \times \text{RD} \\ &= 1000 \text{ kg/m}^3 \times 1.03 \\ &= 1030 \text{ kg/m}^3 \end{aligned}$$

$$\begin{aligned} p &= h\rho g \\ &= 200 \text{ m} \times 1030 \text{ kg/m}^3 \times 9.81 \text{ N/kg} \\ &= \mathbf{2021 \text{ kPa (Ans.)}} \end{aligned}$$



FORCE ON A SUBMERGED SURFACE

As shown above, in any container that contains a liquid, the pressure due to the height (depth) of the liquid is minimum at the top surface of the liquid and maximum at the bottom. For an open container (i.e open to atmosphere), the surface pressure is zero and the pressure at any depth is determined by the above equation: $p = h\rho g$

The pressure of the liquid exerts a force on the submerged surfaces (e.g. sides and bottom) of a container. The force exerted at any point on the surface will vary, increasing proportionally with liquid depth. The overall, resultant force on a vertical surface can be determined by first finding the average pressure and then multiplying by the total area exposed to the liquid. The average pressure will occur at the mid-elevation point between the bottom and top of the liquid. Also, the average pressure will be the average of the top and bottom pressures, which, for an atmospheric container, will be one half of the bottom pressure. Since $F = P \times A$, the resultant force on a submerged surface is: $F = h\rho gA$

Example 4

What is the total force on the bottom and on each side of a tank 6 m by 10 m that holds water to a depth of 5 m?

Solution 4

The pressure at the bottom of the tank is found using equation: $p = h\rho g$

$$\begin{aligned} p &= h\rho g \\ &= 5 \text{ m} \times 1000 \text{ kg/m}^3 \times 9.81 \text{ N/m}^2 \\ &= 49.05 \text{ kPa} \end{aligned}$$

The force on the **bottom** of the tank is determined by equation: $F = pA$

$$\begin{aligned} F &= pA \\ &= 49.05 \text{ kPa} \times (6 \text{ m} \times 10 \text{ m}) \\ &= \mathbf{2943 \text{ kN (Ans.)}} \end{aligned}$$

The average pressure on the sides of the tank is: $49.05/2 = 24.53 \text{ kPa}$.

The force on the **long side** of the tank is:

$$\begin{aligned} F &= pA \\ &= 24.53 \text{ kPa} \times (5 \text{ m} \times 10 \text{ m}) \\ &= \mathbf{1226.5 \text{ kN (Ans.)}} \end{aligned}$$

The force on the **short side** of the tank is:

$$\begin{aligned} F &= pA \\ &= 24.53 \text{ kPa} \times (5 \text{ m} \times 6 \text{ m}) \\ &= \mathbf{735.9 \text{ kN (Ans.)}} \end{aligned}$$

CENTER OF PRESSURE

The **Center of Pressure** on a submerged surface may be defined as the single point on the surface at which the resultant force of the liquid may be considered to be concentrated. The location of the center of pressure is measured from the top of the liquid, along the plane (whether vertical or slanted) of the submerged surface.

The general equation to find center of pressure is: $cp = \frac{I_G \sin \theta}{AH} + \frac{H}{\sin \theta}$

Where: I_G = second moment of area around the centroid of the submerged area. For a rectangular area this is $BD^3/12$.
(B = width; D = depth)

θ = angle from the horizontal of the submerged surface.
(for a vertical surface, $\theta = 90^\circ$ and $\sin \theta = 1$)

A = submerged area

H = height of liquid above the centroid of the submerged area

For a vertical, rectangular surface, if the depth of the liquid is D, the center of pressure is located at $2/3$ D down from the top surface of the liquid.

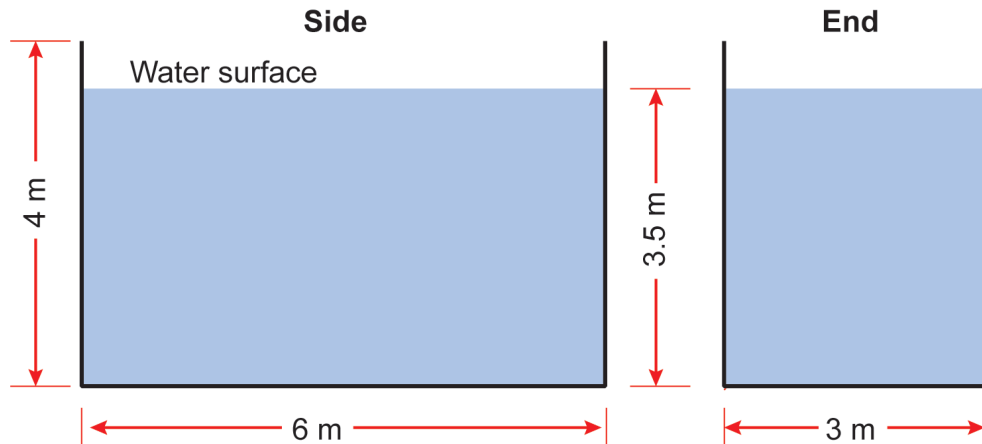
Center of Pressure for a rectangular surface can be demonstrated with the following example problem.

Example 5

An open, rectangular tank has two sides that are 6 m long by 4 m high and two ends that are 3 m wide and 4 m high. What is the location of the center of pressure for each side and for each end if the tank contains 3.5 m of water?

Solution 5

First, draw a simple diagram to represent the tank sides and ends.



For the sides: $A = 6 \times 3.5 = 21 \text{ m}^2$, $H = 3.5/2 = 1.75 \text{ m}$

$$I_G = BD^3/12 = (6 \times 3.5^3)/12 = 21.44$$

For the ends: $A = 3 \times 3.5 = 10.5 \text{ m}^2$, $H = 3.5/2 = 1.75 \text{ m}$

$$I_G = BD^3/12 = (3 \times 3.5^3)/12 = 10.72$$



Since the sides are vertical, $\sin \theta = 1$ and the cp equation can be simplified.

$$\begin{aligned}\text{cp (side)} &= \frac{I_G}{AH} + H \\ &= \frac{21.44}{21 \times 1.75} + 1.75 \\ &= \mathbf{2.33 \text{ m (Ans.)}}\end{aligned}$$

$$\begin{aligned}\text{cp (end)} &= \frac{I_G}{AH} + H \\ &= \frac{10.72}{10.5 \times 1.75} + 1.75 \\ &= \mathbf{2.33 \text{ m (Ans.)}}\end{aligned}$$

OBJECTIVE 3

Explain buoyancy and perform calculations involving buoyancy principles.

BUOYANCY

The ability of an object to float in a liquid is called **buoyancy**. When an object is placed in a liquid, the liquid exerts an upward force on the object; this force is called the **buoyant force**. The magnitude of the upward force is equal to the weight of the volume of fluid that the object displaces. This is called the Archimedes Principle and can be stated in the following equation.

Buoyant force = Specific weight of fluid $\times$ volume of fluid displaced

$$\text{or} \quad F_b = \gamma_f \times V_f$$

In the SI system, the buoyant force, F_b , is in Newtons; specific weight, γ_f , is in N/m^3 ; and fluid volume, V_f , is in m^3 .

With the above in mind, it is recognized that:

- A free object that is floating (partially submerged) in a fluid weighs less than the volume of fluid that it is displacing. The upward buoyant force of the fluid on the object is greater than the downward force of the object.
- A free object that sinks to the bottom of a fluid weighs more than the fluid volume it is displacing. The downward force of the object is greater than the upward buoyant force of the fluid.
- A free object that is fully immersed in a fluid, but not moving, weighs the same as the volume of fluid it is displacing. The downward force of the object equals the upward buoyant force of the fluid.

Another useful relationship when dealing with buoyancy problems, in which an object is floating, is the Law of Equilibrium, which simply states that:

$$\text{Total downward force} = \text{Total upward force.}$$

In buoyancy situations, the total downward force is supplied by the object itself, plus any external downward forces acting upon it, while the total upward forces are the buoyant force, plus any other external upward forces.



Example 6

A vertical float column on the side of a tank is used to indicate the liquid level in the tank. Float is a hollow sphere, with a vertical indicator rod attached to the top so the float raises and lowers the rod. Float is 10 cm in diameter, made of a material that is 2 mm thick and has a density of 2.3 g/cm³. Mass of the indicator rod is 0.7 kg.

- What is the buoyant force exerted by the liquid?
- If the system is designed so the float is exactly half submerged, what is the specific weight of the liquid in the tank?

Solution 6

- The buoyant force exerted by the liquid is equal to the downward force exerted by the float (plus the rod).

Let external radius of the float = R and internal radius = r

$$\begin{aligned}\text{Volume of float material} &= \frac{4}{3} \pi (R^3 - r^3) \\ &= 4.189 [(5 \text{ cm})^3 - (4.8 \text{ cm})^3] \\ &= 60.36 \text{ cm}^3\end{aligned}$$

$$\begin{aligned}\text{Mass of float material} &= 60.36 \text{ cm}^3 \times 2.3 \text{ g/cm}^3 \\ &= 138.83 \text{ g} \\ &= 0.139 \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Total mass} &= \text{mass of float} + \text{mass of rod} \\ &= 0.139 \text{ kg} + 0.7 \text{ kg} \\ &= 0.839 \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Downward force} &= 0.839 \text{ kg} \times 9.81 \text{ N/kg} \\ &= 8.23 \text{ N}\end{aligned}$$

but Buoyant force = Downward force

therefore Buoyant force = **8.23 N (Ans.)**

- Now the buoyancy equation can be rearranged to find the specific weight of the liquid. Note that the volume of liquid displaced is exactly half of the float volume.

$$\begin{aligned}F_b &= \gamma_f \times V_f \\ \text{or } \gamma_f &= \frac{F_b}{V_f} \\ &= \frac{8.23 \text{ N}}{\frac{1}{2} \left(\frac{4}{3} \pi R^3 \right)} \\ &= \frac{8.23 \text{ N}}{0.5 \times 4.189 \times (5 \text{ cm})^3} \\ &= \frac{8.23 \text{ N}}{261.8 \text{ cm}^3} \\ &= 31.14 \times 10^{-3} \text{ N/cm}^3 \\ &= \mathbf{31.14 \text{ kN/m}^3 \text{ (Ans.)}}\end{aligned}$$

OBJECTIVE 4

Define and calculate thermal expansion of a vessel and its liquid contents.

THERMAL EXPANSION

For solids, the expansion of an object is determined using the coefficient of thermal (or linear) expansion. For fluids, volumetric expansion is more appropriate.

The change in volume is found by the equation:

$$\Delta V = V\beta(T_2 - T_1)$$

where β is the coefficient of volumetric (or cubical) expansion (as measured in change in volume per °C). For objects of constant density, expansion is equal in all directions. The coefficient of volumetric expansion (β) is three times that for linear expansion (α). Thus, the equation can also be written as

$$\Delta V = V3\alpha(T_2 - T_1)$$

Example 7

A tank of oil with a volume of 10 m³ is heated from 15°C to 190°C. If the coefficient of volumetric expansion is 0.9×10^{-3} per °C, what is the volume at 190°C?

Solution 7

The change in volume is found using equation: $\Delta V = V\beta(T_2 - T_1)$:

$$\begin{aligned}\Delta V &= V\beta(T_2 - T_1) \\ &= 10 \text{ m}^3 \times (0.9 \times 10^{-3}/^\circ\text{C}) \times (190 - 15)^\circ\text{C} \\ &= 10 \text{ m}^3 \times (0.0009/^\circ\text{C}) \times (175)^\circ\text{C} \\ &= 0.009 \text{ m}^3/^\circ\text{C} \times 175^\circ\text{C} \\ &= 1.575 \text{ m}^3\end{aligned}$$

Therefore, the new volume is:

$$\begin{aligned}V_2 &= V_1 + \Delta V \\ &= 10 \text{ m}^3 + 1.575 \text{ m}^3 \\ &= \mathbf{11.575 \text{ m}^3 \text{ (Ans.)}}\end{aligned}$$



DIFFERENTIAL VOLUMETRIC EXPANSION

If two different materials change in temperature, they will expand or contract at different rates. Since a solid object usually expands less than the fluid it holds, this means that the liquid requires a larger volume. If a tank is almost full, it may overflow if the temperature increases. For the same reason, fluids contained in piping require an overflow tank to prevent spillage.

Example 8

A section of pipe 14 m long, with an internal diameter of 3 cm, is filled with oil and is heated by 28°C. What additional volume has to be accommodated in the system to contain the oil overflow?

Given: Coefficient of thermal expansion for steel - 12×10^{-6} per °C

Coefficient of volumetric expansion for oil - 0.9×10^{-3} per °C

Solution 8

Volume of the piping is

$$\begin{aligned} V &= 1400 \text{ cm} \times \pi (1.5 \text{ cm})^2 \\ &= 9896 \text{ cm}^3 \end{aligned}$$

Increase in the volume of the piping due to the expansion of the steel is found using equation: $\Delta V = V3\alpha(T_2 - T_1)$:

$$\begin{aligned} \Delta V &= V3\alpha(T_2 - T_1): \\ &= 9896 \text{ cm}^3 \times 3 \times 12 \times 10^{-6}/^\circ\text{C} \times 28^\circ\text{C} \\ &= 9896 \text{ cm}^3 \times 0.0000036/^\circ\text{C} \times 28^\circ\text{C} \\ &= 9.975 \text{ cm}^3 \end{aligned}$$

The increase in the volume of the oil is found using equation: $\Delta V = V\beta(T_2 - T_1)$:

$$\begin{aligned} \Delta V &= V\beta(T_2 - T_1) \\ &= 9896 \text{ cm}^3 \times 0.9 \times 10^{-3}/^\circ\text{C} \times 28^\circ\text{C} \\ &= 9896 \text{ cm}^3 \times 0.0009/^\circ\text{C} \times 28^\circ\text{C} \\ &= 249.38 \text{ cm}^3 \end{aligned}$$

The difference in volumes is the oil overflow which is:

$$\begin{aligned} \text{Oil overflow} &= 249.38 - 9.975 \\ &= \mathbf{239.4 \text{ cm}^3 \text{ (Ans.)}} \end{aligned}$$

OBJECTIVE 5

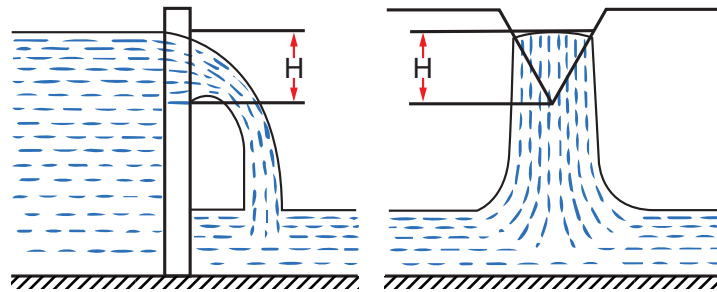
Describe flow in open channels and calculate fluid flow through a weir.

FLOW IN OPEN CHANNELS

One aspect of fluid mechanics, hydraulics, is concerned with liquid flow in open channels. For example, this applies to water supply, drainage and sewage systems, and water cooling systems in industry.

A weir is an obstruction placed across a channel to control flow. It may also be used to measure the flow rate. An example is shown in Figure 2.

Figure 2 – A Weir Used to Measure Flow Rate

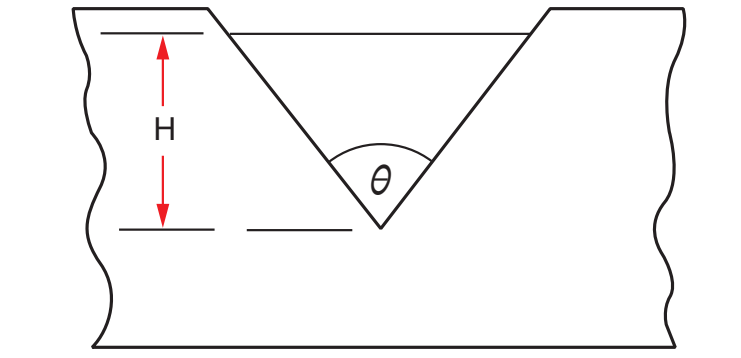


In order to measure the flow, a notch is cut into the weir. The flow rate is a function of the shape of the notch, and the height of the flow through the notch. Rectangular notches are used for larger flow rates. Triangular notches (also called V-notches) are used for lower flow rates.

Triangular Notch (V-Notch)

The geometry of a V-notch is illustrated in Figure 3.

Figure 3 – Geometry of a V-Notch





The general equation for flow through a V-notch is:

$$Q = 2.362 C_d \tan \frac{\theta}{2} H^{\frac{5}{2}}$$

Where flow (Q) is measured in m^3/s , θ is the angle of the notch, and H is the height of the fluid in metres (m), and C_d is the discharge coefficient for the weir. C_d has no units and varies with the liquid and the weir shape. For example, C_d for water generally ranges from 0.55 to 0.65.

Example 9

A triangular weir with a 90° notch is 0.5 m high. What is the maximum flow rate that it can measure if the discharge coefficient is given as 0.62?

Solution 9

Maximum flow will occur when the weir is filled to the top; that is, when $H = 0.5$ m. Therefore:

$$\begin{aligned} Q &= 2.362 C_d \tan \frac{\theta}{2} H^{\frac{5}{2}} \\ &= 2.362 \times 0.62 \times \tan \frac{90^\circ}{2} \times (0.5)^{\frac{5}{2}} \\ &= 2.362 \times 0.62 \times 1 \times 0.1768 \\ &= \mathbf{0.259 \text{ m}^3/\text{s} \text{ (Ans)}} \end{aligned}$$

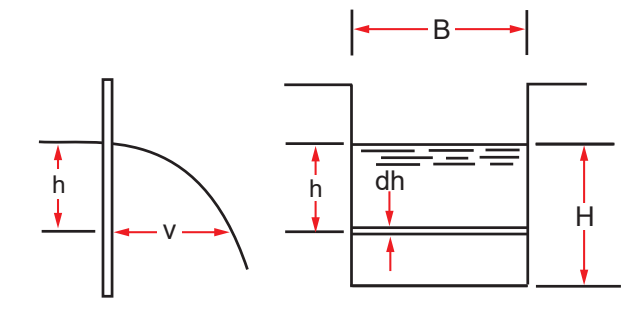
Rectangular Notch

In Figure 4, B is the width of the notch, and H is the height of liquid above the bottom of the notch. To develop an equation for the rectangular notch flow, consider one elemental strip of fluid area at a depth, h , below the surface, with breadth, B , and height, dh . The area of the strip will then be $B \times dh$.

Its velocity of flow, v , will depend on h , such that:

$$\text{Velocity (v)} = \sqrt{2gh}$$

Figure 4 – Rectangular Notch Flow



It follows that the quantity flowing through this strip of area will be:

$$\text{Velocity (v)} \times \text{Area} = \sqrt{2gh} \times Bdh$$

The total flow is the sum of all such strips, from the bottom, where $h = 0$, to the top, where $h = H$, which can be found by calculus, integrating between these limits.

$$\text{Total flow} = \int_0^H \sqrt{2gh} B dh$$

Since B and $2g$ are constant quantities, they can be moved to the front and then the integration completed for h , as follows:

$$\begin{aligned} \text{Flow} &= B\sqrt{2g} \int_0^H h^{\frac{1}{2}} dh \\ &= B\sqrt{2g} \left[\frac{h^{\frac{3}{2}}}{\frac{3}{2}} \right]_0^H \\ &= \frac{2}{3} B \sqrt{2g} H^{\frac{3}{2}} \end{aligned}$$

To make allowance for friction, contraction of flow and approach velocity, a coefficient of discharge, C_d , must be factored into the above formula. This is determined by test for each notch, but will usually range from about 0.59 to 0.62. This gives a final equation:

$$\text{Flow through rectangular notch} = \frac{2}{3} C_d B \sqrt{2g} \times H^{\frac{3}{2}} \text{ m}^3/\text{s}$$

Example 10

A rectangular notch is 6 m wide. It discharges 270 tonnes of water per minute. Calculate the head over the notch if the discharge coefficient is 0.59.

Solution 10

The head over the notch is calculated using:

$$Q = \frac{2}{3} C_d B \sqrt{2g} \times H^{\frac{3}{2}} \text{ m}^3/\text{s}:$$

$$\text{where: } 270 \text{ t/min} = 270 \text{ m}^3/\text{min} = 4.5 \text{ m}^3/\text{s}$$

$$\begin{aligned} Q &= \frac{2}{3} \times C_d \times B \sqrt{2g} \times H^{\frac{3}{2}} \\ &= \frac{2}{3} \times C_d \times B \sqrt{2 \times 9.81} \times H^{\frac{3}{2}} \\ &= \frac{2}{3} \times 0.59 \times 6 \times 4.429 \times H^{\frac{3}{2}} \\ H^{\frac{3}{2}} &= \left(\frac{Q}{\frac{2}{3} \times 0.59 \times 6 \times 4.429} \right) \end{aligned}$$

$$\begin{aligned} H &= \left(\frac{4.5}{\frac{2}{3} \times 0.59 \times 6 \times 4.429} \right)^{\frac{2}{3}} \\ &= \left(\frac{4.5}{10.4524} \right)^{\frac{2}{3}} \\ &= \sqrt[3]{(0.4305)^2} \\ &= 0.5702 \text{ m (Ans.)} \end{aligned}$$



OBJECTIVE 6

Describe liquid flow in a pipe using the continuity equation.

FLOW IN PIPES

Many industrial systems incorporate the flow of liquids through enclosed piping, for example, process, cooling, and lubrication systems.

In this module, flow is assumed to be uniform, steady, and laminar.

Flow is uniform if velocity is aligned with the axis of the pipe, and the flow does not re-circulate.

Flow is steady if it does not vary, or fluctuate, at a specific location with respect to time.

Flow is laminar if it moves in layers (laminae) with straight parallel streamlines. At higher velocities, laminar flow starts to break down and becomes turbulent.

Flow can be measured in one of three ways, by:

- Volume
- Mass
- Weight

Volume Flow Rate

The first method used to measure flow is volume flow rate.

It is calculated by the equation:

$$Q = Av$$

$$Q = \text{Flow rate, m}^3/\text{s}$$

$$A = \text{Cross-sectional area, m}^2$$

$$v = \text{Average velocity across the area, m/s}$$

Since it is common to express volume flow in litres per minute (L/min), it may be necessary to convert using the equation:

$$Q(\text{L/min}) = Q(\text{m}^3/\text{s}) \times 60 (\text{s/min}) \times 1000 (\text{L/m}^3)$$

Mass Flow Rate

The second method, mass flow rate, is given by the equation

$$M = \rho Q$$

$$M = \text{Mass flow rate, kg/s}$$

$$\rho = \text{Density, kg/m}^3$$

$$Q = \text{Flow rate, m}^3/\text{s}$$

Weight Flow Rate

The third method, weight flow rate, is given by the equation

$$W = \gamma Q$$

$$W = \text{Weight flow rate, N/s}$$

$$\gamma = \text{Specific weight of the fluid, N/m}^3$$

$$Q = \text{Flow rate, m}^3/\text{s}$$

Example 11

A pipe of 10 cm internal diameter carries oil with a relative density of 0.87 at a velocity of 1 m/s. What is the flow rate in terms of volume (both m³/s and L/min), weight, and mass?

Solution 11

Area of the pipe is:

$$\begin{aligned} A &= \pi r^2 \\ &= \pi (0.05 \text{ m})^2 \\ &= 0.0079 \text{ m}^2 \end{aligned}$$

Volume flow rate in m³/s is given by the equation:

$$\begin{aligned} Q &= Av \\ &= 0.0079 \text{ m}^2 \times 1 \text{ m/s} \\ &= \mathbf{0.0079 \text{ m}^3/\text{s}} \end{aligned}$$

Volume flow in L/min is given by the equation:

$$\begin{aligned} Q(\text{L/min}) &= Q(\text{m}^3/\text{s}) \times 60 (\text{s/min}) \times 1000 (\text{L/m}^3): \\ Q &= Q(\text{m}^3/\text{s}) \times 60 (\text{s/min}) \times 1000 (\text{L/m}^3) \\ &= 0.0079 \text{ m}^3/\text{s} \times 60 \text{ s/min} \times 1000 \text{ L/m}^3 \\ &= \mathbf{474.00 \text{ L/min (Ans.)}} \end{aligned}$$

The density of the oil is obtained from the equation:

$$\begin{aligned} \text{R.D.} &= \frac{\rho}{1000 \text{ kg/m}^3} \\ \rho &= \text{R.D.} \times 1000 \text{ kg/m}^3 \\ &= 0.87 \times 1000 \text{ kg/m}^3 \\ &= 870 \text{ kg/m}^3 \end{aligned}$$



The **mass flow rate** is given by the equation:

$$\begin{aligned}
 M &= \rho Q \\
 &= 870 \text{ kg/m}^3 \times 0.0079 \text{ m}^3/\text{s} \\
 &= \mathbf{6.8730 \text{ kg/s (Ans.)}}
 \end{aligned}$$

The specific weight is calculated using the equation $\gamma = 9.81 \text{ (kN/m}^3) \times \text{RD}$:

$$\begin{aligned}
 &= 9.81 \times 0.87 \text{ kN/m}^3 \\
 &= 8.5347 \text{ kN/m}^3
 \end{aligned}$$

The **weight flow rate** is given by equation, $W = \gamma Q$:

$$\begin{aligned}
 &= 8.5347 \text{ kN/m}^3 \times 0.0079 \text{ m}^3/\text{s} \\
 &= 0.0674 \text{ kN/s} \\
 &= \mathbf{67.40 \text{ N/s (Ans.)}}
 \end{aligned}$$

PRINCIPLE OF CONTINUITY

The principle of continuity is a simple approach to analyzing flow in pipes. It is based on the law of conservation of mass which states that mass flow is the same at all points in a piping system as long as there are no junctions. Thus, mass flow rates are equal for any two points in a piping system, or

$$M_1 = M_2$$

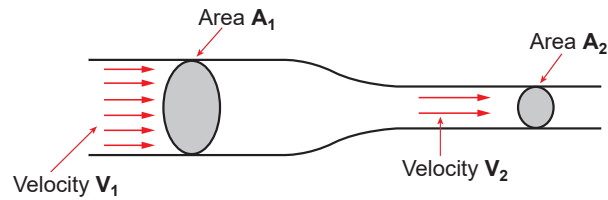
By substituting the equation for volume flow rate, $Q = Av$, into the one for mass flow rate, $M = \rho Q$, the equation becomes:

$$\begin{aligned}
 &M_1 = M_2 \\
 \text{but } &M_1 = \rho_1 Q_1 \quad \text{and} \quad M_2 = \rho_2 Q_2 \\
 \text{so } &\rho_1 Q_1 = \rho_2 Q_2 \\
 \text{but } &Q_1 = A_1 v_1 \quad \text{and} \quad Q_2 = A_2 v_2 \\
 \text{and } &\rho_1 A_1 v_1 = \rho_2 A_2 v_2
 \end{aligned}$$

For liquid flow, the densities at any two points are the same. Therefore, the densities may be cancelled and the continuity equation becomes:

$$A_1 v_1 = A_2 v_2$$

Figure 5 – Simple Flow in a Pipe Showing the Principle of Continuity



Note: These equations work well for liquids, but should only be used for gases with low velocity.

Example 12

A pipe, with an internal diameter of 10 cm, carries water with a velocity of 1 m/s. What is the velocity if the pipe size is reduced to 5 cm?

Solution 12

Area of the 10 cm pipe is:

$$\begin{aligned} A_1 &= \pi r^2 \\ &= \pi (0.05 \text{ m})^2 \\ &= 0.0079 \text{ m}^2 \end{aligned}$$

Area of the 5 cm pipe is:

$$\begin{aligned} A_2 &= \pi r^2 \\ &= \pi (0.025 \text{ m})^2 \\ &= 0.0020 \text{ m}^2 \end{aligned}$$

Velocity in the 5 cm pipe is calculated, using the equation:

$$\begin{aligned} A_1 v_1 &= A_2 v_2 \\ v_2 &= \frac{A_1 v_1}{A_2} \\ &= \frac{0.0079 \text{ m}^2 \times 1 \text{ m/s}}{0.0020 \text{ m}^2} \\ &= 3.95 \text{ m/s (Ans.)} \end{aligned}$$



OBJECTIVE 7

Apply the law of conservation of energy to fluid flow and define Bernoulli's equation.

LAW OF CONSERVATION OF ENERGY

A more complete method of analyzing fluid flow is to apply the law of conservation of energy. It states that the total amount of energy in a fluid system remains constant, assuming that no energy is supplied to or removed from the system.

There are three forms of energy that can be exchanged in a fluid system depending on its configuration.

It can be expressed as:

- Potential energy
- Kinetic energy
- Flow energy

Potential Energy

The first form of energy is potential energy (PE or E_p). Potential energy is the energy that is stored, or available, in a body due to its position or condition. A body with potential energy is at rest, but if released from its position it will perform work. It is solely due to the body's position that the potential for work exists. The work is done against the force of gravity. Potential energy represents the work required to elevate a mass of fluid over a vertical distance (h).

It is calculated using the equation:

$$E_p = mgh$$

Kinetic Energy

The second form of energy is kinetic energy (KE or E_k). Kinetic energy may be defined as the energy stored in a body due to its motion. By virtue of its motion, such a body has available energy stored up in the event that the force causing motion is removed.

It can be expressed as:

$$E_k = \frac{1}{2}mv^2$$

Flow Energy

The third form of energy is flow energy which is due to pressure.

It is expressed as:

$$E_f = PV$$

BERNOULLI'S PRINCIPLE

For the total energy to be conserved, it is possible to write an equation for any two points in the fluid system (see Figure 6) which results in the equations:

$$E_1 = E_2$$

$$E_{f1} + E_{p1} + E_{k1} = E_{f2} + E_{p2} + E_{k2}$$

$$\text{but } E_p = mgh, E_k = \frac{1}{2}mv^2, \text{ and } E_f = PV$$

By substitution, the energy equation becomes:

$$P_1V_1 + m_1gh_1 + \frac{1}{2}m_1v_1^2 = P_2V_2 + m_2gh_2 + \frac{1}{2}m_2v_2^2$$

Further development of this equation (not shown here) results in the following Bernoulli Equation.

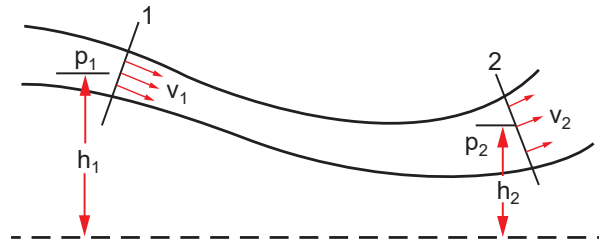
$$h_1 + \frac{P_1}{w} + \frac{V_1^2}{2g} = h_2 + \frac{P_2}{w} + \frac{V_2^2}{2g}$$

Where:

- w = the force of gravity on 1 m³ of fluid (N/m³ or kN/m³)
- h = height (in metres) above a datum level
- P = pressure (N/m², i.e. Pa, or kN/m², i.e. kPa)
- v = velocity of the fluid (m/s, metres/second)

On each side of the Bernoulli Equation, the first term (h) represents elevation head, the second term (P/w) represents pressure head, and the third term ($v^2/2g$) represents velocity head.

Figure 6 – Fluid Elements Used in Bernoulli's Principle



It is important to recognize the restrictions on Bernoulli's principle, namely:

1. It applies only to incompressible fluids since it assumes that the relative density remains the same.
2. The flow must be steady and not change with respect to time.
3. There cannot be any mechanical device between the two locations that adds or extracts energy from the flow.
4. There can be no heat transferred into or out of the system.
5. There can be no energy lost due to friction.

When evaluating a flow problem, it is often possible to ignore one or more terms in the equation. For example, if the points are taken at a free surface, the pressure will be zero and the pressure head is assumed to be zero. Velocity will also be zero at a free surface.



Example 13

Water flows through a horizontal pipe, which varies in diameter. At one location, the pressure is 140 kPa and the velocity is 1.5 m/s. If the velocity is 15 m/s at another location, what is the pressure?

Solution 13

Since there is no change in elevation, the elevation head can be ignored and the equation can be written as:

$$\frac{P_1}{w} + \frac{v_1^2}{2g} = \frac{P_2}{w} + \frac{v_2^2}{2g}$$

from which

$$\begin{aligned}
 P_2 &= \left(\frac{P_1}{w} + \frac{v_1^2}{2g} - \frac{v_2^2}{2g} \right) w \\
 &= \left(\frac{140 \text{ kPa}}{9.81 \text{ kN/m}^3} + \frac{(1.5 \text{ m/s})^2}{2 \times 9.81 \text{ m/s}^2} - \frac{(15 \text{ m/s})^2}{2 \times 9.81 \text{ m/s}^2} \right) \times 9.81 \text{ kN/m}^3 \\
 &= \left(\frac{140 \text{ kN/m}^2}{9.81 \text{ kN/m}^3} + \frac{2.25 \text{ m}^2/\text{s}^2}{19.62 \text{ m/s}^2} - \frac{225 \text{ m}^2/\text{s}^2}{19.62 \text{ m/s}^2} \right) \times 9.81 \text{ kN/m}^3 \\
 &= (14.271 \text{ m} + 0.115 \text{ m} - 11.468 \text{ m}) \times 9.81 \text{ kN/m}^3 \\
 &= 2.917 \text{ m} \times 9.81 \text{ kN/m}^3 \\
 &= 28.62 \text{ kN/m}^2 = \mathbf{28.62 \text{ kPa (Ans.)}}
 \end{aligned}$$

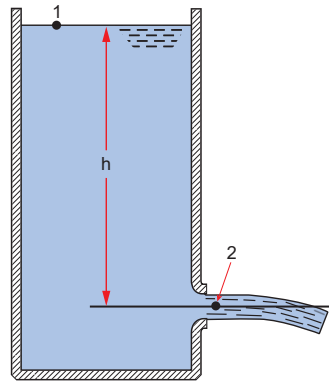
OBJECTIVE 8

Calculate fluid flow from a vessel orifice.

FLOW FROM A VESSEL ORIFICE

Flow from a vessel, such as a tank, often occurs from an orifice at the bottom, such as the one shown in Figure 7.

Figure 7 – Flow from a Vessel



The velocity, and thus the flow, can be calculated using Bernoulli's equation. Looking at the three terms in Bernoulli's equation, it can be seen that at point 1 (in Figure 7), the only term that remains is potential energy, or elevation head. At point 2, the pressure term is zero (using atmospheric pressure as the base). The resulting equation is therefore:

$$h_1 + \frac{P_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{P_2}{\rho g} + \frac{v_2^2}{2g}$$

$$h_1 - h_2 = \frac{v_2^2}{2g}$$

If the difference in height, $h_1 - h_2$, is indicated by h , by rearranging the equation, the velocity becomes:

$$h_1 - h_2 = \frac{v_2^2}{2g}$$

but $h_1 - h_2 = h$

so $h = \frac{v_2^2}{2g}$

$$v_2^2 = 2g \times h$$

$$v_2 = \sqrt{2gh}$$



The flow through the opening is derived by substituting $v_2 = \sqrt{2gh}$ into the equation $Q = A_2v_2$ so that the volume flow is:

$$\begin{aligned} Q &= A_2v_2 \\ \text{but } v_2 &= \sqrt{2gh} \\ \text{so } Q &= A_2\sqrt{2gh} \end{aligned}$$

In practice, the velocity is somewhat less, and the flow is reduced because the effective area is smaller due to contraction of the jet flow. This leads to the need for a coefficient of discharge (always less than 1) to allow for correction. Equation then becomes:

$$Q = C_d A \sqrt{2gh}$$

Example 14

Water flows from a 10 cm diameter hole in the side of a tank, 6 m below the water surface. If the coefficient of discharge is 0.6, what is the flow?

Solution 14

Area of the orifice is:

$$\begin{aligned} A &= \pi r^2 \\ &= \pi (0.05 \text{ m})^2 \\ &= 0.0079 \text{ m}^2 \end{aligned}$$

Flow is obtained from the equation:

$$\begin{aligned} Q &= C_d A \sqrt{2gh} \\ &= 0.6 \times 0.0079 \text{ m}^2 \sqrt{2 \times 9.81 \text{ m/s}^2 \times 6 \text{ m}} \\ &= 0.0047 \text{ m}^2 \sqrt{117.72 \text{ m}^2/\text{s}^2} \\ &= 0.0047 \text{ m}^2 \times 10.8499 \text{ m/s} \\ &= 0.0510 \text{ m}^3/\text{s} \\ &= \mathbf{51.0 \text{ L/s (Ans.)}} \end{aligned}$$

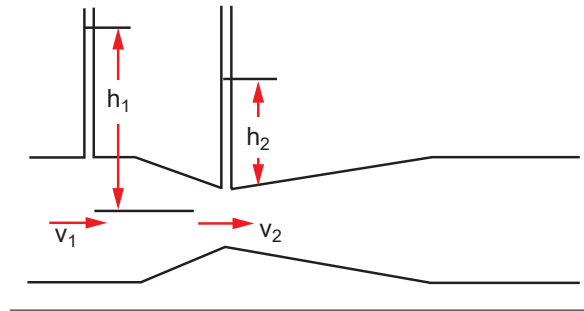
OBJECTIVE 9

Calculate flow using a venturi meter.

VENTURI METERS

Bernoulli's principle can be used to measure flow rates using a range of devices based on the fact that flow can be correlated to the drop in pressure due to an increase in flow velocity. One such device is the venturi meter shown in Figure 8.

Figure 8 – Venturi Meter



Flow rate can be derived from a combination of Bernoulli's equation and the equation of continuity.

Bernoulli's equation can be written without the elevation head terms since the change in elevation is zero when the venturi meter is horizontal (and is still quite small even when it is installed vertically).

The resulting equation is:

$$\frac{P_1}{w} + \frac{v_1^2}{2g} = \frac{P_2}{w} + \frac{v_2^2}{2g}$$

If the cross-sectional areas are A_1 and A_2 , the equation of continuity can be written as:

$$A_1 v_1 = A_2 v_2$$

$$v_2 = \frac{A_1 v_1}{A_2}$$



Substituting this in Bernoulli's equation: $h_1 + \frac{P_1}{w} + \frac{v_1^2}{2g} = h_2 + \frac{P_2}{w} + \frac{v_2^2}{2g}$, we can solve for velocity at point 1 (Figure 6) as follows:

$$\frac{P_1}{w} + \frac{v_1^2}{2g} = \frac{P_2}{w} + \frac{v_2^2}{2g}$$

$$\frac{P_1}{w} - \frac{P_2}{w} = \frac{v_2^2}{2g} - \frac{v_1^2}{2g}$$

$$2g \frac{(P_1 - P_2)}{w} = v_2^2 - v_1^2$$

But $v_2 = \frac{A_1 v_1}{A_2}$

$$\frac{2g(P_1 - P_2)}{w} = \left(\frac{A_1 v_1}{A_2} \right)^2 - v_1^2$$

$$\frac{2g(P_1 - P_2)}{w} = v_1^2 \left(\frac{A_1^2}{A_2^2} - 1 \right)$$

$$v_1 = \sqrt{\frac{2g(P_1 - P_2)}{w \left(\frac{A_1^2}{A_2^2} - 1 \right)}}$$

Flow rate can be calculated from velocity by the equation: $Q = Av$, with the addition of a coefficient of discharge to account for the fact that there are some minor losses, so that:

$$Q = A_1 v_1 \times C_d$$

but $v_1 = \sqrt{\frac{2g(P_1 - P_2)}{w \left(\frac{A_1^2}{A_2^2} - 1 \right)}}$

so $Q = A_1 C_d \sqrt{\frac{2g(P_1 - P_2)}{w \left(\frac{A_1^2}{A_2^2} - 1 \right)}}$

Example 15

A venturi meter with a pipe diameter of 30 cm and a throat diameter of 15 cm is used to determine the flow rate of water. If the pressures are measured as 138 kPa and 117 kPa, respectively, and the coefficient of discharge is 0.98, what is the flow rate, in L/min?

Solution 15

Find the area of the pipe:

$$\begin{aligned} A_1 &= \pi r^2 \\ &= \pi (0.15 \text{ m})^2 \\ &= 0.0707 \text{ m}^2 \end{aligned}$$

Find the area of the throat:

$$\begin{aligned} A_2 &= \pi r^2 \\ &= \pi (0.075 \text{ m})^2 \\ &= 0.0177 \text{ m}^2 \end{aligned}$$

Now use the equation:

$$Q = A_1 C_d \sqrt{\frac{2g(P_1 - P_2)}{\frac{w}{A_1^2} - 1}}$$

Where $w = 9.81 \text{ kN/m}^3$

$P_1 = 138 \text{ kN/m}^2$

$P_2 = 117 \text{ kN/m}^2$

$C_d = 0.98$

$$Q = A_1 C_d \sqrt{\frac{2g(P_1 - P_2)}{\frac{w}{A_1^2} - 1}}$$

$$= 0.0707 \text{ m}^2 \times 0.98 \sqrt{\frac{2 \times 9.81 \text{ m/s}^2 (138 \text{ kN/m}^2 - 117 \text{ kN/m}^2)}{\frac{9.81 \text{ kN/m}^3}{(0.0707 \text{ m}^2)^2} - 1}}$$

$$= 0.0693 \text{ m}^2 \sqrt{\frac{19.62 \text{ m/s}^2 \times 21 \text{ kN/m}^2}{\frac{9.81 \text{ kN/m}^3}{15}}}$$

$$= 0.0693 \text{ m}^2 \sqrt{\frac{42 \text{ m}^2/\text{s}^2}{15}}$$

$$= 0.0693 \text{ m}^2 \sqrt{2.8 \text{ m}^2/\text{s}^2}$$

$$= 0.0693 \text{ m}^2 \times 1.6733 \text{ m/s}$$

$$= 0.1160 \text{ m}^3/\text{s}$$



Convert this to litres/minute:

$$\begin{aligned} Q &= 0.1160 \text{ m}^3/\text{s} \times 1000 \text{ L/m}^3 \times 60 \text{ s/min} \\ &= \mathbf{6960 \text{ L/min (Ans)}} \end{aligned}$$

CHAPTER QUESTIONS

1. A tank contains a 5400 kg mass of oil, which has a relative density of 0.86. What is the volume of the oil?
2. What is the total force on the bottom and on each side of a tank 2 m by 3 m containing water to a depth of 1 m?
3. A tank of oil with a volume of 5 m³ heats up from 20°C to 120°C. If the coefficient of volumetric expansion is 0.9×10^{-3} per °C, what is the volume at 120°C?
4. A rectangular notch is 7 m wide. The head of water over the rectangular notch is 0.85 metres. Calculate the amount of water it discharges per minute if the discharge coefficient is 0.62.
5.
 - a) Explain the principle of flow continuity
 - b) A pipe with 20 cm internal diameter carries water with velocity of 2 m/s. What is the velocity if the pipe size is reduced to 10 cm?
6. Water flows through a horizontal pipe, which varies in diameter. At one point, the pressure is 225 kPa and the velocity is 2.45 m/s. If the pressure is 30 kPa at another location, what is the velocity?
7. Water flows from a 20 cm diameter hole in the side of a tank, 5 m below the water surface. If the coefficient of discharge is 0.7, what will be the flow?
8. A venturi meter with a pipe diameter of 30 cm and a throat diameter of 16 cm is used to determine the flow rate of water. If pressures are measured as 140 kPa and 120 kPa, respectively, and flow rate is 7000 L/min, what is the coefficient of discharge?
9. A large water reservoir has a rectangular underground drain channel, 1.5 m wide by 1.25 m high, with a sliding, rectangular gate valve. When the bottom of the gate is 4 m below the water surface in the reservoir, where is the center of pressure on the gate?
10. An object is floating freely in a liquid that has a density of 0.94 kg/litre. Total volume of the liquid is 0.55 m³ and 2/3 of it is submerged in the liquid. What is the mass of the object?

