National Qualifications 2024

X823/77/11 Engineering Science

FRIDAY, 17 MAY
9:00 AM – 11:30 AM

Total marks — 75

You may refer to the Advanced Higher Engineering Science Data Booklet.

SECTION 1 — 35 marks

Attempt ALL questions.

SECTION 2 — 40 marks

Attempt ALL questions.

Write your answers clearly in the answer booklet provided. In the answer booklet, you must clearly identify the question number you are attempting.

For questions 1 (a), 4 (a) and 8 (e), write your answers clearly in the worksheets provided in the answer booklet.

Show all working and units where appropriate.

The number of significant figures expressed in a final answer should be equivalent to the least significant data value given in the question. Answers that have two more figures or one less figure than this will be accepted.

Use **blue** or **black** ink. Sketches, diagrams and graphs may be drawn in pencil.

Before leaving the examination room you must give your answer booklet to the Invigilator; if you do not, you may lose all the marks for this paper.

MARKS

SECTION 1 — 35 marks

Attempt ALL questions

1. During the construction of a city bypass, a project manager divided part of the project into eight stages, A–H, identified the precedents for each stage, and the planned duration of each stage. The information is detailed in the precedence table below.

Stage	Precedence	Duration (weeks)
A	--	4
B	--	5
C	--	3
D	B	3
E	B, C	7
F	A, D	3
G	E, F	3
H	F	5

(a) Using the precedence table and the **worksheet for question 1 (a)**:

(i) complete the Gantt chart for stages E, F, G and H of the project, showing the timing of each stage including floats **3**

(ii) identify the critical path for this project. **1**

The project manager listed several costs associated with this part of the project:

- preliminary site work (to ensure compliance with health and safety legislation)
- construction materials
- travel expenses of engineers and technicians
- engineering, technical and construction worker salaries
- employer National Insurance contributions.

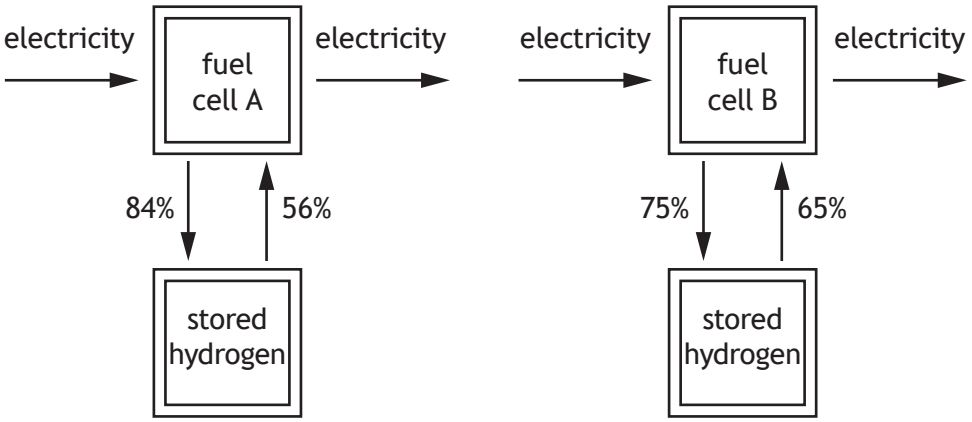
(b) (i) Describe what is meant by the terms ‘direct cost’ and ‘on-cost’. **2**

(ii) Identify one direct cost and one on-cost from the list above. **1**

MARKS

2. A fuel cell is a device that can extract hydrogen from water using electricity. The hydrogen can be stored. The fuel cell can also generate electricity from the stored hydrogen when electricity is required.

The diagram below shows the conversion efficiencies for two fuel cell designs.



Determine which of fuel cells A or B has the higher efficiency overall. Show all working. **3**

[Turn over

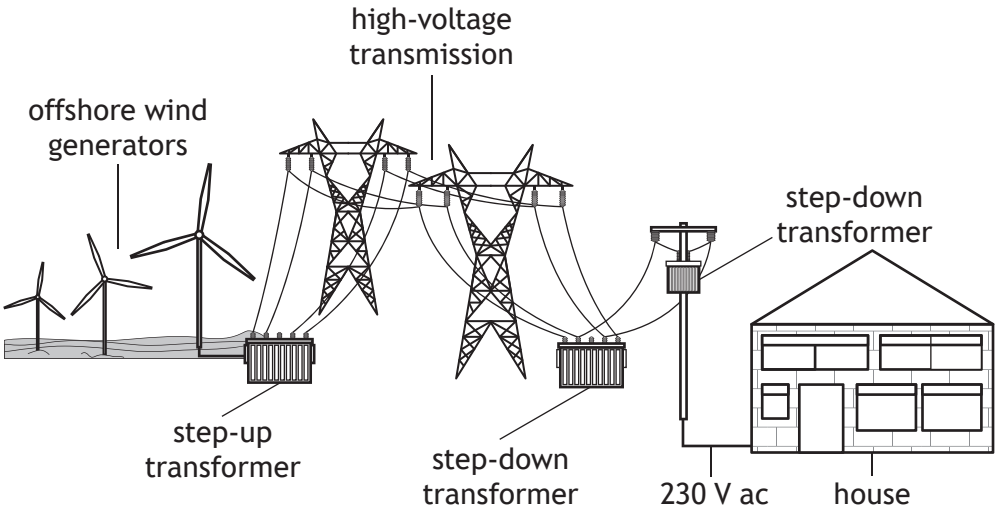
MARKS

3. UK homes and business are supplied with electricity from the national grid. The national grid obtains its electricity from a wide range of sources.

(a) Describe the difference between base and peak demand on the national grid. **1**

(b) State one method of power generation used specifically to meet base demand. **1**

A simplified diagram for power transmission is shown below.



(c) Explain why step-up and step-down transformers are necessary in power transmission. **2**

Power losses in a power line with multiple cores are given by the formula below.

$$P = \frac{1000\ NI^2\rho L}{A}$$

where:

- P — losses in kilowatts (kW)
- N — number of cores
- I — current flow in amps (A)
- ρ — resistance per unit length in ohms per meter ($\Omega\,m^{-1}$), determined by material. Typical values are:

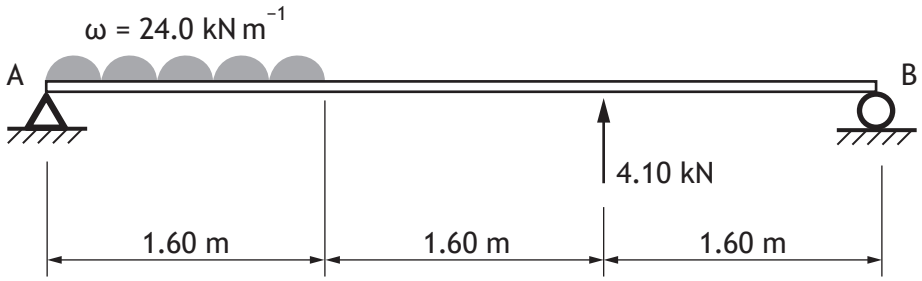
  copper $1.68 \times 10^{-8}\ \Omega\,m^{-1}$ and aluminium $2.82 \times 10^{-8}\ \Omega\,m^{-1}$
- L — length of cable in metres (m)
- A — area of cable in square millimetres (mm^2)

17 kW is supplied to a consumer through a 550 m, three-core copper power line, cross section of 45 mm^2 carrying 40.0 A current flow.

(d) Calculate the efficiency of the power line. **2**

MARKS

4. A simply supported beam is shown below.



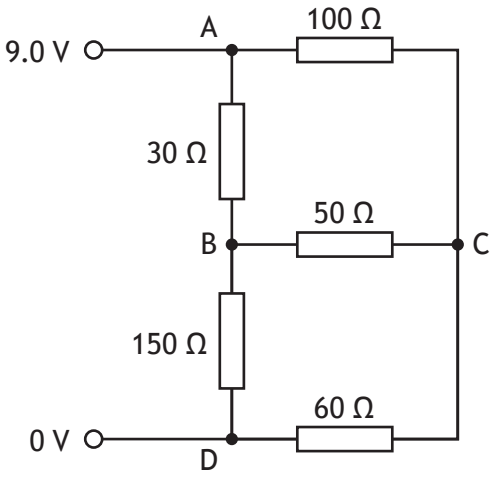
(a) Draw a shear force diagram for this simply supported beam on the **worksheet for question 4 (a)**. **4**

(b) Explain why a point where the graph of shear force crosses the horizontal axis of the shear force diagram is important to the designer of the beam. **2**

[Turn over

MARKS

5. A student's circuit is shown below.



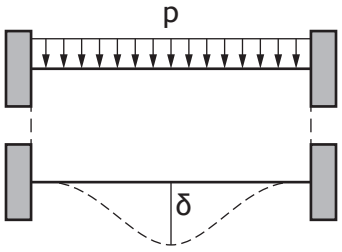
Resistor values are accurate to the nearest ohm.

Calculate, using nodal analysis, the voltage at nodes B and C. **5**

MARKS

6. An open cylindrical storage tank has a base made of a circular disc, joined around the edge to the vertical wall of the tank.

The maximum deflection, δ, of a disc of radius, r, that is clamped around the edge under a uniformly applied pressure, p ($N\,m^{-2}$), is given by the equation:



$$\delta = \frac{pr^4}{64Z}$$

where Z is a term called the flexural rigidity of the disc given by the equation:

$$Z = \frac{Et^3}{12(1-\nu^2)}$$

and

r = radius of disc

E = Young's modulus

t = thickness of disc

ν = Poisson's ratio (a material property)

The tank holds water that produces a pressure of 100.0 $kN\,m^{-2}$ on its base of diameter 2.00 m. The tank is made from mild steel that has a Poisson's ratio of 0.30.

Calculate the thickness of the base of the tank required if the maximum deflection is to be limited to 15 mm. **4**

[Turn over

MARKS

7. A student has developed a prototype to model a DC motor on a golf trolley. They have written a sub-procedure to control the motor speed. The motor driver is controlled via output pin 3 of a microcontroller.

ARDUINO

```
void sub_procedure_A()
{
        for(int x = 250; x >= 1; x = x−5)
        {
          duty = x;

          analogWrite(3, duty);


          for(int y = 1; y <= x; y++)
            {

              delay(1);
            }
        }
}
```

PBASIC

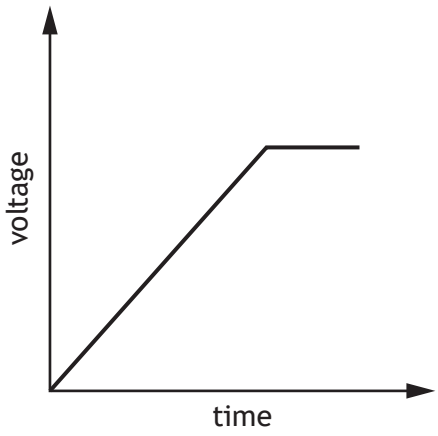
```
sub_procedure_A:

for x = 250 to 1 step −5

    duty = x * 4

    pwmout B.3, 255, duty


    for y = 1 to x

        pause 1

    next y

next x

return
```

The graphs shown on the page opposite are sketches of voltage change as a function of time.

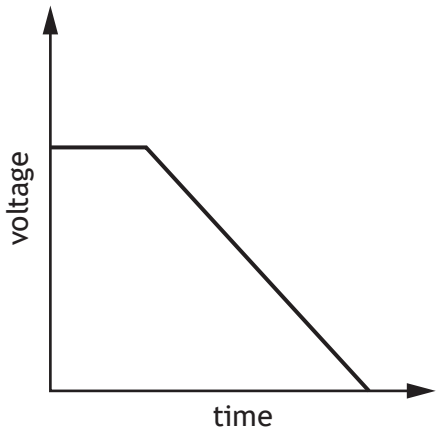
State which of these graphs would most closely represent the voltage change that the sub-procedure would produce at pin 3 of the microcontroller. Justify your answer, referring to the outer and the inner counted loops. **4**

7. (continued)

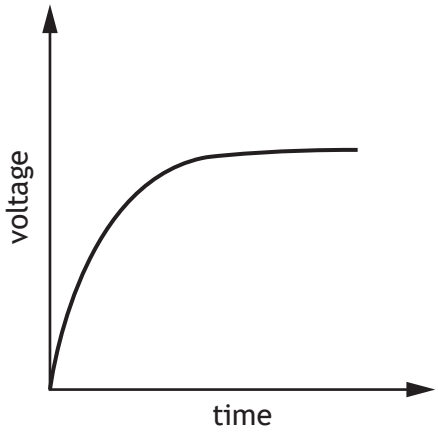
graph 1



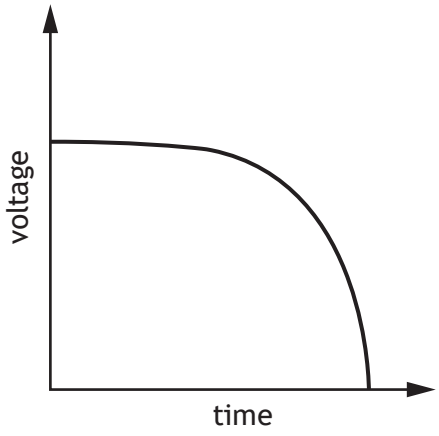
graph 2



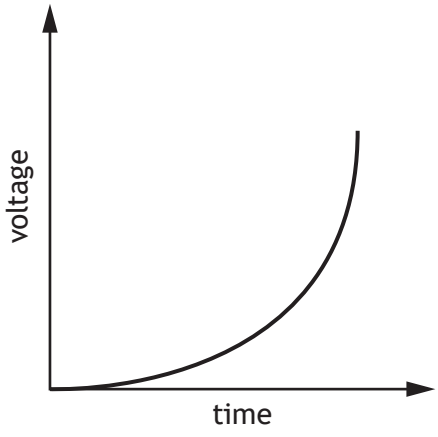
graph 3



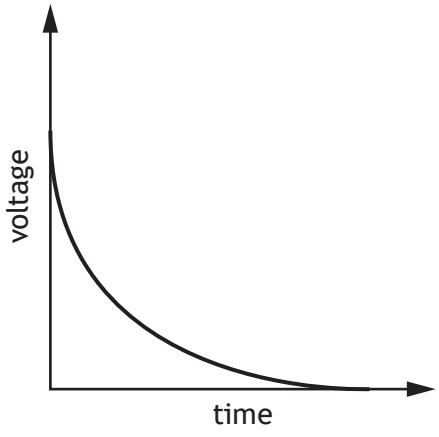
graph 4



graph 5



graph 6



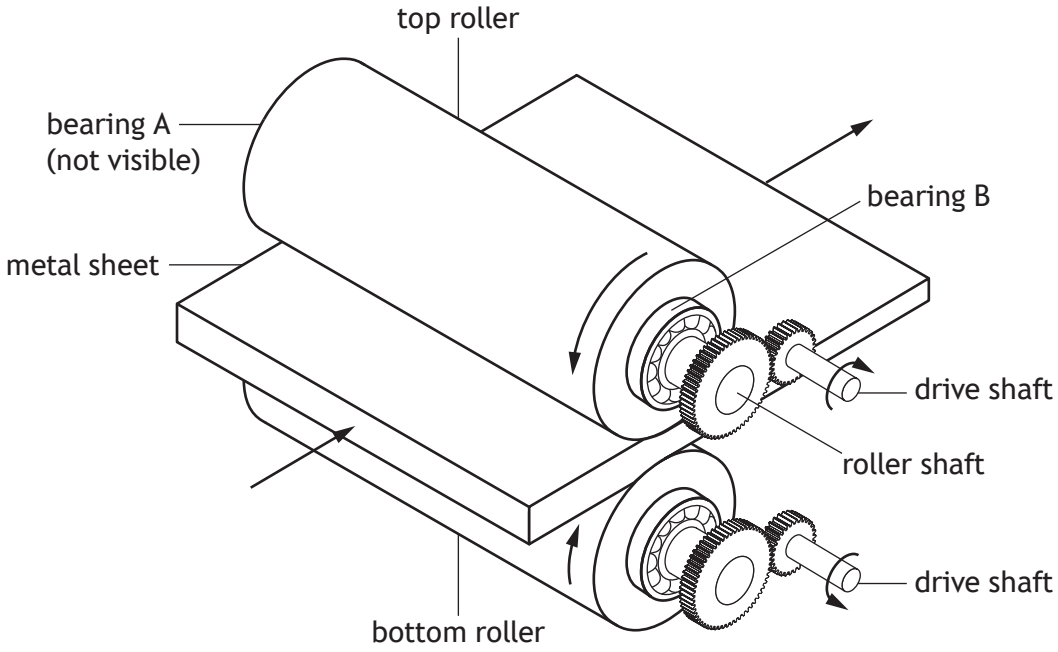
[Turn over

MARKS

SECTION 2 — 40 marks

Attempt ALL questions

8. The manufacture of metal sheets involves the process of rolling to achieve a reduction in thickness. A 1.0 m wide sheet of bronze is reduced in thickness by passing through a pair of rollers. Each roller is turned by an electric motor.



The roller shafts are supported on bearings at each end.

For each roller, 12 kW of power is transferred through simple spur gears. The drive gear has a pitch circle diameter of 75 mm, the driven gear on the roller has a pitch circle diameter of 125 mm, and the pressure angle is 20.0°.

The rollers rotate at 120 revs min^{-1}.

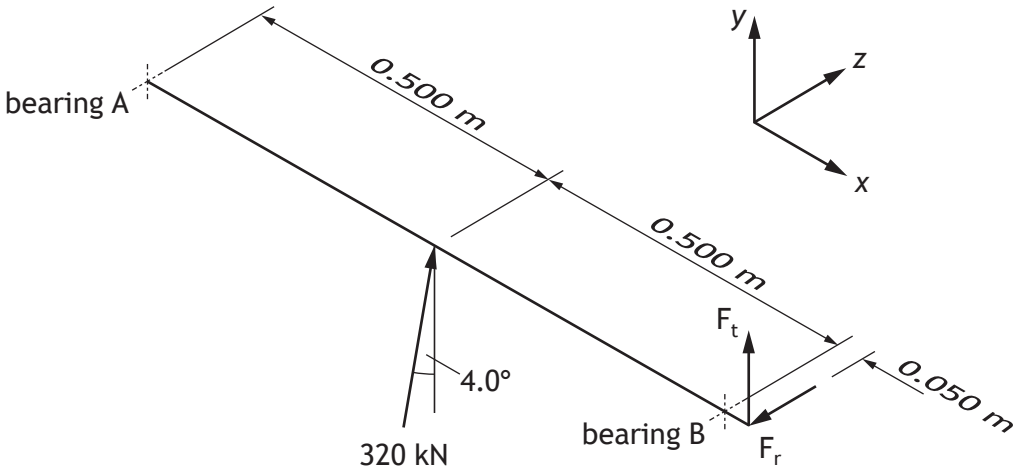
(a) Calculate the tangential (F_t) and radial (F_r) forces which act on the driven gear attached to the top roller. **3**

8. (continued)

When rolling a sheet of a different metal, the motors supply more power and the magnitude of the contact force at the spur gear mesh is 20.3 kN. The pressure angle remains 20.0°.

The force on the top roller is uniformly distributed across the width of the roller and is represented by a point load of 320 kN acting at 4.0° from the vertical.

The arrangement of these loads on the roller shaft is given in the diagram below. F_r is the radial component and F_t is the tangential component of the contact force at the gear mesh.

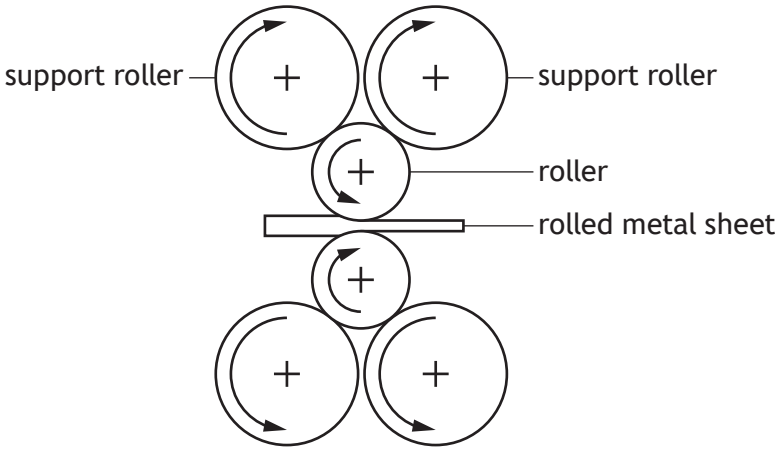


(b) Calculate the magnitude and direction of the force acting on bearing B. **6**

[Turn over

8. (continued)

It is advantageous to keep the diameter of the roller small because the force on the roller is reduced. Therefore, less power is required to roll the metal. However, larger diameter support rollers which contact the top of the roller must then be included, as shown below.



(c) Explain why the support rollers become necessary if the roller diameter is reduced. **2**

The speed of the rollers is displayed on a speed display sub-system.

A +5.0 V signal from a digital source is input to an op-amp integrator circuit.

When the +5.0 V signal is first connected to the integrator, the value of the output voltage, V_{out}, is 0 V.

The longer the signal is high, the larger the output from the integrator circuit will be.

The circuit must produce a +7.5 V output after 250 ms.

The capacitor value in the integrator circuit is 6.8 μF.

(d) (i) Calculate the value of resistor R in the integrator circuit. **3**

(ii) Draw an op-amp circuit to meet this specification. Include values for all components. **2**

8. (continued)

The output from the integrator sub-system is used as an input to an analogue to digital converter (ADC), which then controls the display. A block diagram for the ADC is given on the **worksheet for Q8 (e)**.

The signal is processed by the ADC to produce a 4-bit binary signal proportional to the speed of the rollers.

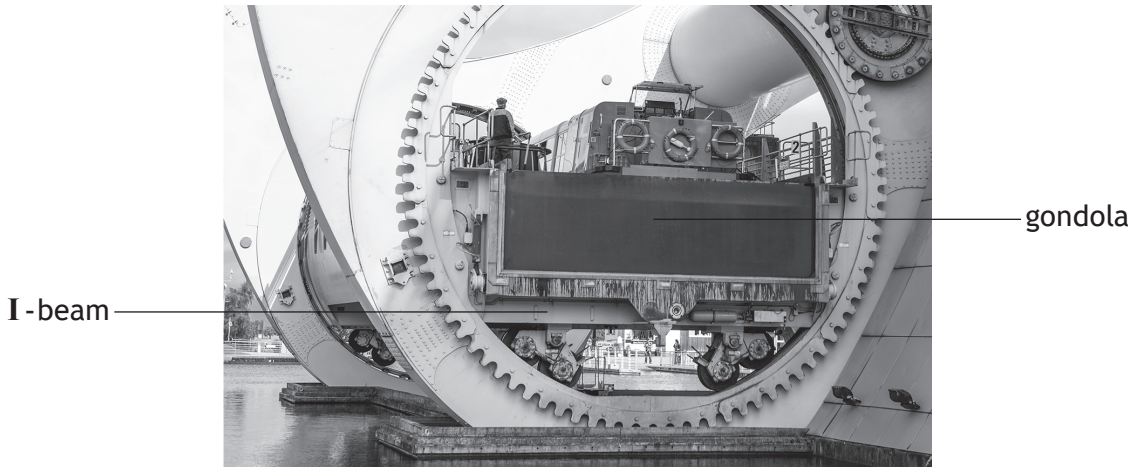
The ADC meets the following specification points:

- The digital output value of 1111 is equivalent to an input voltage, V_{signal}, of 10.0 V.
- Output A is the least-significant bit (lsb), and output D is the most-significant bit (msb).
- The D-A converter within the ADC has a feedback resistor of 160 kΩ.
- Binary counter outputs are each 5.0 V or 0 V.

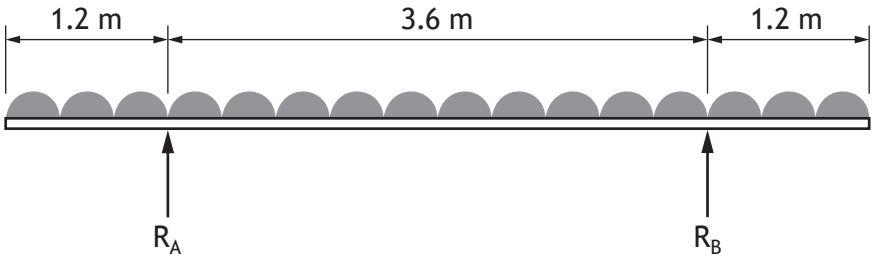
(e) Complete the circuit diagram for the D-A converter used within the ADC on the **worksheet for question 8 (e)**. Include the required value for each resistor in the circuit and show all the calculations used to determine these values. **4**

[Turn over

9. The Falkirk Wheel transfers canal boats between two canals at different elevations. The canal boats are held in large tanks, called gondolas, as they are raised or lowered.



The gondolas are carried by two low-alloy steel **I**-beams. The mass of the gondola and its contents is 480 tonnes (1 tonne = 1000 kg), and it can be assumed that each beam takes an equal share of the load. The load on one beam is shown in the free-body diagram below.



The reactions provided by the simple supports are indicated by R_A and R_B.

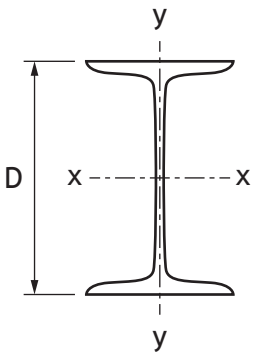
(a) Determine the bending moment at x = 0 m, x = 1.2 m and x = 3 m, where x is the distance measured from the left-hand end of the beam. Show all working. **5**

9. (continued)

The low-alloy steel **I**-beam is assumed to operate subject to a maximum bending moment of 368 kN m and a required factor of safety of 2.5.

(b) Determine the most appropriate **I**-beam cross-section from the table below. Show all working. **4**

	Depth, D (mm)	Mass per unit length ($kg\,m^{-1}$)	2nd Moment of area ($\times 10^4\ mm^4$)	
			Axis x–x	Axis y–y
1	406	67	24502	1365
2	406	74	27481	1546
3	457	67	29597	1452
4	457	74	33536	1672



[Turn over

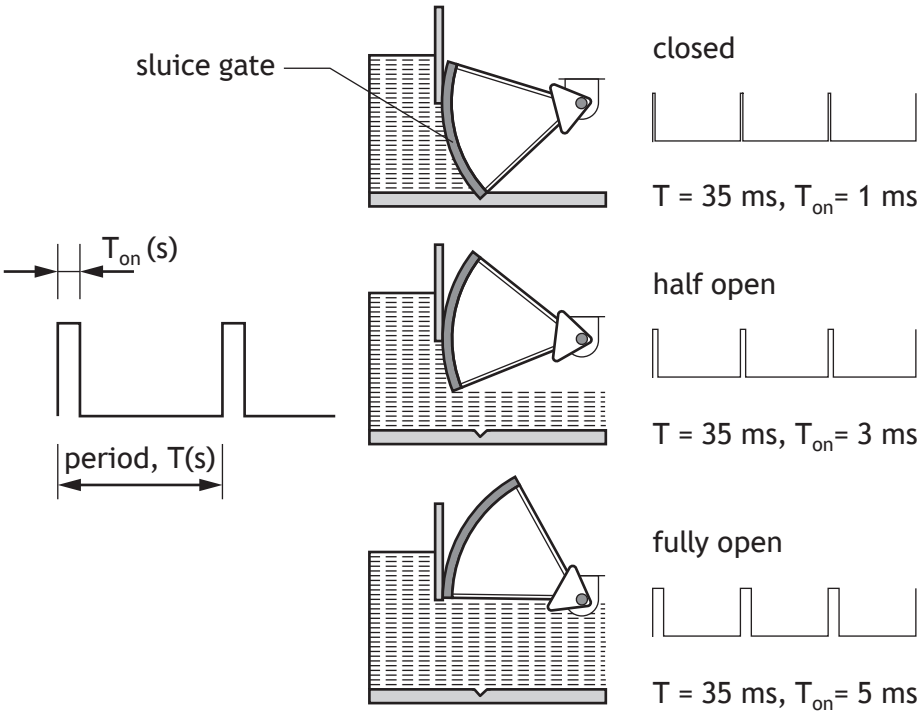
9. (continued)

In 2021 funding was announced for the Falkirk Wheel visitor centre's existing gas boilers to be replaced with solar panels and air-source heat pumps to reduce its carbon footprint.

(c) Describe how one sustainability factor could be considered in the design of these replacement technologies. **2**

Water level must be controlled for the Falkirk Wheel to operate. A student investigated controlling water flowrate to a tank using a rotating sluice gate.

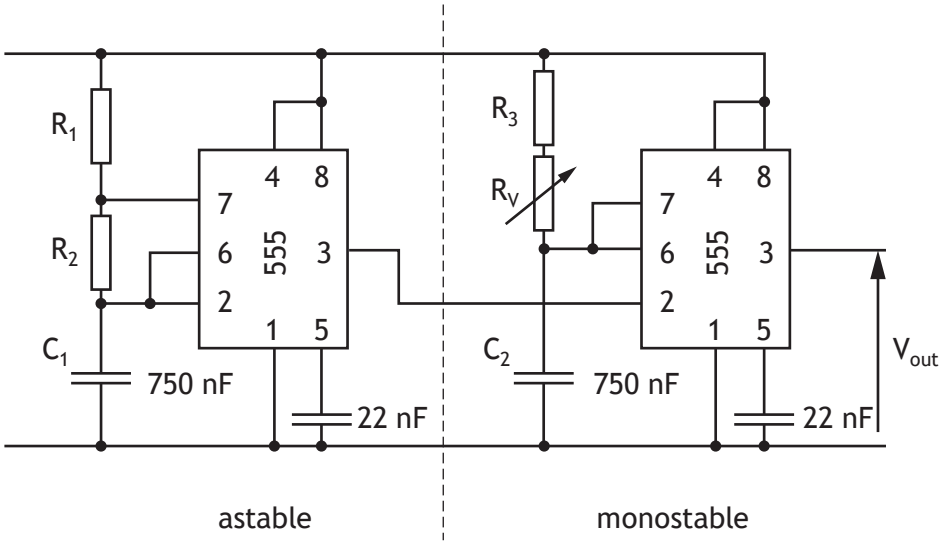
A servomotor controls the gate position. The angular position of the servomotor depends on the length of an electrical pulse it receives every 35 ms.



MARKS

9. (continued)

The circuit below produces the waveform to control the angular position of the servomotor.



The astable circuit produces a pulse at pin 3 with a period of 35 ms and a duty cycle that is 98% of the pulse period.

(d) Determine the values of the resistors R_1 and R_2. Show all working. **2**

The negative edge of each astable pulse triggers the monostable, and its output, V_{out}, goes high for a time given by

$$T_{on} = 1.1(R_3 + R_V)C_2$$

The variable resistor, R_V, allows the length of the pulse, T_{on}, to be varied.

(e) Determine the values of the resistors R_3 and R_V. Show all working. **3**

[Turn over

9. (continued)

The student chose to replace the hard-wired circuit with a microcontroller and a different servomotor.

Using values set by a rotary potentiometer, the program produces a waveform to set the required position of the gate.

The programmable control system was intended to meet the following specification points:

- The gate is fully closed when the potentiometer angle is 230° and fully open when the potentiometer angle is 310°.
- The potentiometer angle range is 0° to 359°.
- The voltage from the potentiometer is processed by the microcontroller's ADC producing a value stored in the integer variable 'input_angle' in the range 0–255.
- Potentiometer rotation of 359° would produce a value of 255 for the variable 'input_angle'.

The period of the waveform is 20 ms.

ARDUINO	**PBASIC**
delayMicroseconds(us) Parameters us — is a variable/constant (0–16383) which specifies the number of microseconds to pause	**pausemicro** microseconds Parameters microseconds — is a variable/constant (0–16383) which specifies the number of microseconds to pause
input_angle **mark** **space** All variables are integers in the range (–32768 to 32767)	**input_angle** **mark** **space** All variables are word integers in the range (0–65535)

9. (continued)

	ARDUINO	**PBASIC**

Section A	void sub_procedure_A()
	{
	input_angle = analogRead(A0)/4;
		sub_procedure_A:
		
		readadc C.1, input_angle

Section B	if(input_angle < 163)
	{
	input_angle = 163;
	}
	
	if(input_angle > 220)
	{
	input_angle = 220;
	}
		if input_angle < 163 then
		
		let input_angle = 163
		
		elseif input_angle > 220 then
		
		let input_angle = 220
		
		endif

Section C	mark = input_angle *100/255*10;
	
	space = 20000 − mark;
	
	digitalWrite(3, HIGH);
	delayMicroseconds(mark);
	
	digitalWrite(3, LOW);
	delayMicroseconds(space);
	}
		let mark = input_angle*100/255*10
		
		let space = 20000 − mark
		
		high B.3
		pausemicro mark
		
		low B.3
		pausemicro space
		
		return

(f) Explain the function of Section B of the program. **2**

When tested, Section C of the program did not produce the intended digital pulse on output pin 3.

(g) Explain why this section of the program does not produce the intended digital pulse. **2**

[END OF QUESTION PAPER]

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