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## Chapter 8. Combustion and Incineration

### Practice Problems

1.

Methane (MW = 16.043) with a heating value of 24,000 Btu/lbm (55.8 MJ/kg) is burned with a 50% efficiency. If the heat of vaporization of any water vapor formed is recovered, approximately how much water (specific heat of 1 Btu/lbm-°F (4.1868 kJ/kg·°C)) can be heated from 60°F to 200°F (15°C to 95°C) when 7 ft<sup>3</sup> (200 L) of methane at 60°F and 14.73 psia (288.9K and 101.51 kPa) are burned?

(A)

25 lbm (11 kg)

(B)

35 lbm (16 kg)

(C)

50 lbm (23 kg)

(D)

95 lbm (43 kg)

2.

15 lbm/hr (6.8 kg/h) of propane (C<sub>3</sub>H<sub>8</sub>, MW = 44.097) is burned stoichiometrically in air. Approximately what volume of dry carbon dioxide (CO<sub>2</sub>, MW = 44.011) is formed after cooling to 70°F (21°C) and 14.7 psia (101 kPa)?

(A)

180 ft<sup>3</sup>/hr (5.0 m<sup>3</sup>/h)

(B)

270 ft<sup>3</sup>/hr (7.6 m<sup>3</sup>/h)

(C)

390 ft<sup>3</sup>/hr (11 m<sup>3</sup>/h)

(D)

450 ft<sup>3</sup>/hr (13 m<sup>3</sup>/h)

3.

In a particular installation, 30% excess air at 15 psia (103 kPa) and 100°F (40°C) is needed for the combustion of methane. Approximately how much nitrogen (MW = 28.016) passes through the furnace if methane is burned at the rate of 4000 ft<sup>3</sup>/hr (31 L/s)?

(A)

270 lbm/hr (0.033 kg/s)

(B)

930 lbm/hr (0.11 kg/s)

(C)

1800 lbm/hr (0.22 kg/s)

(D)

2700 lbm/hr (0.34 kg/s)

4.

Approximately how much air is required to completely burn one unit mass of a fuel that is 84% carbon, 15.3% hydrogen, 0.3% sulfur, and 0.4% nitrogen by weight?

(A)

9 lbm air/lbm fuel (9 kg air/kg fuel)

(B)

12 lbm air/lbm fuel (12 kg air/kg fuel)

(C)

15 lbm air/lbm fuel (15 kg air/kg fuel)

(D)

18 lbm air/lbm fuel (18 kg air/kg fuel)

5.

Propane ( $C_3H_8$ ) is burned with 20% excess air. The gravimetric percentage of carbon dioxide in the flue gas is most nearly

(A)

8%

(B)

12%

(C)

15%

(D)

22%

6.

The ultimate analysis of a coal is 80% carbon, 4% hydrogen, 2% oxygen, and the rest ash. The flue gases are 60°F and 14.7 psia (15.6°C and 101.3 kPa) when sampled, and are 80% nitrogen, 12% carbon dioxide, 7% oxygen, and 1% carbon monoxide by volume. The air required to burn 1 lbm (1 kg) of coal under these conditions is most nearly

(A)

11 lbm (11 kg)

(B)

15 lbm (15 kg)

(C)

19 lbm (19 kg)

(D)

23 lbm (23 kg)

[7.](#)

The ultimate analysis of a coal is 75% carbon, 5% hydrogen, 3% oxygen, 2% nitrogen, and the rest ash. Atmospheric air is 60°F (16°C) and at standard pressure. Assuming the lower heating value of this fuel is 12,957 Btu/lbm (30.14 MJ/kg), the theoretical temperatures of the combustion product is most nearly

(A)

3500°F (1900°C)

(B)

4000°F (2200°C)

(C)

4500°F (2500°C)

(D)

5000°F (2800°C)

[8.](#)

An anhydrous fuel oil has the following ultimate analysis: 85.43% carbon, 11.31% hydrogen, 2.7% oxygen, 0.34% sulfur, and 0.22% nitrogen. The oil is burned with 60% excess air. The mass of wet flue gas produced per kg of fuel burned is most nearly

(A)

18 kg

(B)

23 kg

(C)

30 kg

(D)

38 kg

[9.](#)

The ultimate analysis of a coal is 51.45% carbon, 16.69% ash, 15.71% moisture, 7.28% oxygen, 4.02% hydrogen, 3.92% sulfur, and 0.93% nitrogen. 15,395 lbm (6923 kg) of the coal are burned, and 2816 lbm (1267 kg) of ash containing 20.9% carbon (by weight) are recovered. 13.3 lbm (kg) of dry gases are produced per pound (kilogram) of fuel burned. The air used per unit mass of fuel is most nearly

(A)

13 lbm air/lbm fuel (13 kg air/kg fuel)

(B)

14 lbm air/lbm fuel (14 kg air/kg fuel)

(C)

15 lbm air/lbm fuel (15 kg air/kg fuel)

(D)

17 lbm air/lbm fuel (17 kg air/kg fuel)

[10.](#)

A coal is 65% carbon by weight. During combustion, 3% of the coal is lost in the ash pit. Combustion uses 9.87 lbm (kg) of air per pound (kg) of fuel. The flue gas analysis is 81.5% nitrogen, 9.5% carbon dioxide, and 9% oxygen. The percentage of excess air by mass is most nearly

(A)

10%

(B)

30%

(C)

70%

(D)

140%

[11.](#)

A coal has an ultimate analysis of 67.34% carbon, 4.91% oxygen, 4.43% hydrogen, 4.28% sulfur, 1.08% nitrogen, and the rest ash. 3% of the carbon is lost during combustion. The flue gases are 81.9% nitrogen, 15.5% carbon dioxide, 1.6% carbon monoxide, and 1% oxygen by volume. The heat produced from the combustion of carbon monoxide is most nearly

(A)

600 Btu/lbm

(B)

800 Btu/lbm

(C)

1000 Btu/lbm

(D)

1200 Btu/lbm

[12.](#)

A natural gas is 93% methane, 3.73% nitrogen, 1.82% hydrogen, 0.45% carbon monoxide, 0.35% oxygen, 0.25% ethylene, 0.22% carbon dioxide, and 0.18% hydrogen sulfide by volume. The gas is burned with 40% excess air. Atmospheric air is 60°F and at standard atmospheric pressure. The theoretical air requirements are most nearly

(A)

5 ft<sup>3</sup> air/ft<sup>3</sup> fuel

(B)

7 ft<sup>3</sup> air/ft<sup>3</sup> fuel

(C)

9 ft<sup>3</sup> air/ft<sup>3</sup> fuel

(D)

13 ft<sup>3</sup> air/ft<sup>3</sup> fuel

[13.](#)

A coal has a gravimetric analysis of 83% carbon, 5% hydrogen, 5% oxygen, and 7% noncombustible matter. 10% of the fired coal mass, including all of the noncombustible matter, is recovered in the ash pit. 26 lbm (26 kg) of air at 70°F (21°C) and 1 atmosphere are used per lbm (kg) of coal burned. When loaded into the furnace, the coal temperature is 60°F (15.6°C). The stack gas from coal combustion has a temperature of 550°F (290°C). The percentage of the combustion heat carried away by the stack gases, based on the coal's as-delivered properties, is most nearly

(A)

18%

(B)

24%

(C)

37%

(D)

49%

[14.](#)

A utility boiler burns coal with an ultimate analysis of 76.56% carbon, 7.7% oxygen, 6.1% silicon, 5.5% hydrogen, 2.44% sulfur, and 1.7% nitrogen. 410 lbm/hr of refuse are removed with a composition of 30% carbon and 0% sulfur. All the sulfur and the remaining carbon are burned. The power plant has the following characteristics.

- coal feed rate: 15,300 lbm/hr

- electric power rating: 17 MW
- generator efficiency: 95%
- steam generator efficiency: 86%
- cooling water rate: 225 ft<sup>3</sup>/sec

The emission rate of solid particulates in lbm/hr is most nearly

(A)

23 lbm/hr

(B)

150 lbm/hr

(C)

810 lbm/hr

(D)

1700 lbm/hr

[15.](#)

250 SCFM (118 L/s) of propane are mixed with an oxidizer consisting of 60% oxygen and 40% nitrogen by volume in a proportion resulting in 40% excess oxygen by weight. The maximum velocity for the two reactants when combined is 400 ft/min (2 m/s) at 14.7 psia (101 kPa) and 80°F (27°C). Maximum velocity for the products is 800 ft/min (4 m/s) at 8 psia (55 kPa) and 460°F (240°C). The minimum size of the inlet pipe is most nearly

(A)

9 ft<sup>2</sup> (0.9 m<sup>2</sup>)

(B)

11 ft<sup>2</sup> (1.1 m<sup>2</sup>)

(C)

14 ft<sup>2</sup> (1.3 m<sup>2</sup>)

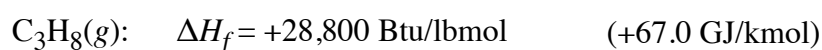
(D)

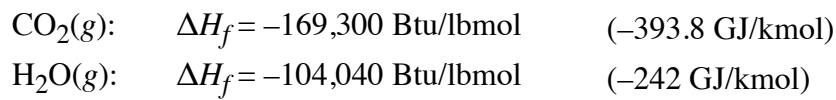
17 ft<sup>2</sup> (1.6 m<sup>2</sup>)

[16.](#)

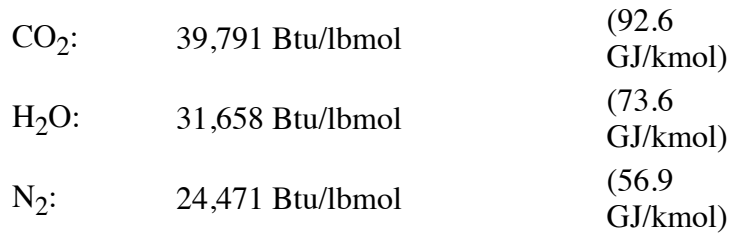
An industrial process uses hot gas at 3600°R (1980°C) and 14.7 psia (101 kPa). It is proposed that propane be burned stoichiometrically in a mixture of nitrogen and oxygen. After passing through the process, gas will be exhausted through a duct, being cooled slowly to 100°F (38°C) and 14.7 psia (101 kPa) before discharge. The following data are available.

- The enthalpies of formation (at the standard reference temperature) are





- The enthalpy increases from the standard reference temperature to 3600°R (1980°C) are



What are most nearly the combining weights of the nitrogen and oxygen, respectively, per pound-mole of propane?

(A)

760 lbm/lbmol, 128 lbm/lbmol (760 kg/kmol, 128 kg/kmol )

(B)

810 lbm/lbmol, 160 lbm/lbmol (810 kg/kmol, 160 kg/kmol)

(C)

845 lbm/lbmol, 160 lbm/lbmol (845 kg/kmol, 160 kg/kmol)

(D)

850 lbm/lbmol, 160 lbm/lbmol (850 kg/kmol, 160 kg/kmol)

[17.](#)

An electrical power-generating plant burns refuse-derived fuel (RDF). After sorting, incoming refuse is shredded and compressed before being fed into the combustor. The raw refuse averages 7% by weight incombustible solids. 5000 lbm/hr of processed RDF produces 20,070 lbm/hr of saturated steam at 200 lbf/in<sup>2</sup>. The combustion products are used to heat incoming feedwater to a saturated temperature of 160°F before entering the combustor. 2000 lbm/hr of water vapor condense in the feedwater heater at a partial pressure of 4 lbf/in<sup>2</sup> and are removed. All thermal losses are to be disregarded. What is most nearly the higher heating value of the RDF?

(A)

4300 Btu/lbm

(B)

4700 Btu/lbm

(C)

4900 Btu/lbm

(D)

5100 Btu/lbm

Solutions

1.

*Customary U.S. Solution*

As in *NCEES Handbook: Temperature*,

$$T = 60^{\circ}\text{F} + 460^{\circ} = 520^{\circ}\text{R}$$

$$p = 14.73 \text{ psia}$$

The molecular weight of methane can be found in *NCEES Handbook: Physical Properties of Liquids and Gases—Temperature-Independent Properties (U.S. Units)*. The mass is

$$\begin{aligned} m &= \frac{pVM}{RT} = \frac{\left(14.73 \frac{\text{lbf}}{\text{in}^2}\right) \left(12 \frac{\text{in}}{\text{ft}}\right)^2 (7 \text{ ft}^3) \left(16.043 \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545.35 \frac{\text{ft}\cdot\text{lbf}}{\text{lbm}\cdot^{\circ}\text{R}}\right) (520^{\circ}\text{R})} \\ &= 0.296 \text{ lbm} \end{aligned}$$

The combustion energy available from methane is

$$\begin{aligned} Q &= \eta m (\text{HHV}) = (0.5) (0.296 \text{ lbm}) \left(24,000 \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 3552 \text{ Btu} \end{aligned}$$

As in *NCEES Handbook: Heat Capacity/Specific Heat ( $c_p$ )*, this energy is used to heat water from 60°F to 200°F.

$$\begin{aligned} Q &= m_{\text{water}} c_p (T_2 - T_1) \\ m_{\text{water}} &= \frac{3552 \text{ Btu}}{\left(1 \frac{\text{Btu}}{\text{lbm}\cdot^{\circ}\text{F}}\right) (200^{\circ}\text{F} - 60^{\circ}\text{F})} \\ &= 25.37 \text{ lbm} \quad (25 \text{ lbm}) \end{aligned}$$

The answer is (A).

*SI Solution*

The molecular weight of methane can be found in *NCEES Handbook: Physical Properties of Liquids and Gases—Temperature-Independent Properties (SI Units)*. The mass is

$$\begin{aligned} m &= \frac{pVM}{RT} \\ &= \frac{(101.51 \text{ kPa}) \left(1000 \frac{\text{Pa}}{\text{kPa}}\right) (200 \text{ L}) \left(16.043 \frac{\text{g}}{\text{mol}}\right)}{\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right) (288.9 \text{ K}) \left(1000 \frac{\text{L}}{\text{m}^3}\right)} \\ &= 0.136 \text{ kg} \end{aligned}$$

The combustion energy available from methane is

$$\begin{aligned} Q &= \eta m (\text{HHV}) \\ &= (0.5) (0.136 \text{ kg}) \left(55.8 \frac{\text{MJ}}{\text{kg}}\right) \left(1000 \frac{\text{kJ}}{\text{MJ}}\right) \\ &= 3794 \text{ kJ} \end{aligned}$$

As in *NCEES Handbook: Heat Capacity/Specific Heat ( $c_p$ )*, this energy is used to heat water from 15°C to 95°C.



$$Q = m_{\text{water}} c_p (T_2 - T_1)$$

$$m_{\text{water}} = \frac{3794 \text{ kJ}}{\left(4.1868 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}}\right) (95^\circ\text{C} - 15^\circ\text{C})}$$

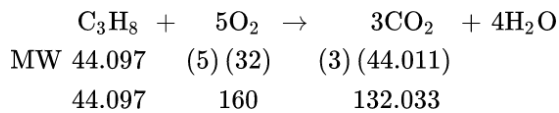
$$= 11.33 \text{ kg} \quad (11 \text{ kg})$$

The answer is (A).

2.

### Customary U.S. Solution

The molecular weights can be found in table MERM24007 (also *NCEES Handbook: Physical Properties of Liquids and Gases—Temperature-Independent Properties*). The combustion reaction should lead to CO<sub>2</sub> and H<sub>2</sub>O as the products. Use the balanced chemical reaction equation from table CERM24007. When properly balanced,



The amount of carbon dioxide produced is 132.033 lbm/44.097 lbm propane. For 15 lbm/hr of propane, the amount of carbon dioxide produced is

$$\left(\frac{132.033 \text{ lbm}}{44.097 \text{ lbm}}\right) \left(15 \frac{\text{lbm}}{\text{hr}}\right) = 44.91 \text{ lbm/hr}$$

As in *NCEES Handbook: Temperature*,

$$T = 70^\circ\text{F} + 460^\circ = 530^\circ\text{R}$$

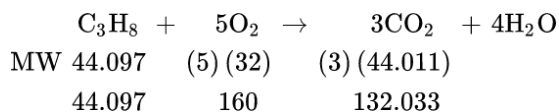
$$\dot{V} = \frac{\dot{m}RT}{pM} = \frac{\left(44.91 \frac{\text{lbm}}{\text{h}}\right) \left(1545.35 \frac{\text{ft-lbf}}{\text{lbmol} \cdot ^\circ\text{R}}\right) (530^\circ\text{R})}{\left(14.7 \frac{\text{lbf}}{\text{in}^2}\right) \left(12 \frac{\text{in}}{\text{ft}}\right)^2 \left(44.011 \frac{\text{lbm}}{\text{lbmol}}\right)}$$

$$= 394.8 \text{ ft}^3/\text{hr} \quad (390 \text{ ft}^3/\text{hr})$$

The answer is (C).

### SI Solution

The molecular weights can be found in table CERM24007 (also *NCEES Handbook* table “Temperature-Independent Properties of Liquids and Gases (SI Units)”). The combustion reaction should lead to CO<sub>2</sub> and H<sub>2</sub>O as the products. Use the balanced chemical reaction equation from table CERM24007. When properly balanced,



The amount of carbon dioxide produced is 132.033 kg/44.097 kg propane. For 6.8 kg/h of propane, the amount of carbon dioxide produced is

$$\left(\frac{132.033 \text{ kg}}{44.097 \text{ kg}}\right) \left(6.8 \frac{\text{kg}}{\text{h}}\right) = 20.36 \text{ kg/h}$$

As in *NCEES Handbook: Temperature*,

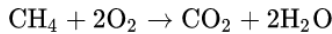
$$T = 21^\circ\text{C} + 273^\circ = 294\text{K}$$

$$\begin{aligned}\dot{V} &= \frac{\dot{m}RT}{pM} = \frac{\left(20.36 \frac{\text{kg}}{\text{h}}\right)\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(294\text{K})}{(101\,000 \text{ Pa})\left(44.011 \frac{\text{g}}{\text{mol}}\right)} \\ &= 11.20 \text{ m}^3/\text{h} \quad (11 \text{ m}^3/\text{h})\end{aligned}$$

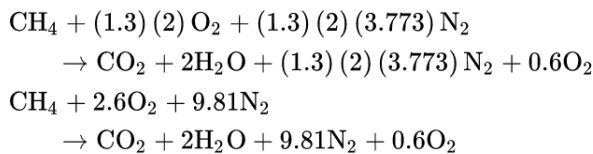
The answer is (C).

3.

The molecular weights can be found in *NCEES Handbook* table “Temperature-Independent Properties of Liquids and Gases (U.S. Units).” Use the balanced chemical reaction equation from table CERM24007. The combustion reaction should lead to CO<sub>2</sub> and H<sub>2</sub>O as the products. When properly balanced,



Use table CERM24006 and table CERM24007 (also *NCEES Handbook: Combustion Reactions* and *NCEES Handbook: Dry Atmospheric Air Composition*). With 30% excess air and considering that there are 3.773 volumes of nitrogen for every volume of oxygen, the reaction equation is



*Customary U.S. Solution*

The volume of nitrogen that accompanies 4000 ft<sup>3</sup>/hr of entering methane is

$$\begin{aligned}V_{\text{N}_2} &= \left(9.81 \frac{\text{ft}^3 \text{ N}_2}{\text{ft}^3 \text{ CH}_4}\right) \left(4000 \frac{\text{ft}^3 \text{ CH}_4}{\text{hr}}\right) \\ &= 39,240 \text{ ft}^3 \text{ N}_2/\text{hr}\end{aligned}$$

This is the “partial volume” of nitrogen in the input stream. As in *NCEES Handbook: Temperature*, the absolute temperature is

$$T = 100^\circ\text{F} + 460^\circ = 560^\circ\text{R}$$

$$\begin{aligned}\dot{m} &= \frac{p\dot{V}M}{RT} \\ &= \frac{\left(15 \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \frac{\text{in}}{\text{ft}}\right)^2\left(39240 \frac{\text{ft}^3}{\text{hr}}\right)\left(28.016 \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545.35 \frac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot^\circ\text{R}}\right)(560^\circ\text{R})} \\ &= 2744 \text{ lbm/hr} \quad (2700 \text{ lbm/hr})\end{aligned}$$

The answer is (D).

*SI Solution*

The volume of nitrogen that accompanies 31 L/s of entering methane is

$$\frac{\left(9.81 \frac{\text{m}^3 \text{ N}_2}{\text{m}^3 \text{ CH}_4}\right) \left(31 \frac{\text{L CH}_4}{\text{s}}\right)}{1000 \frac{\text{L}}{\text{m}^3}} = 0.3041 \text{ m}^3/\text{s}$$

This is the “partial volume” of nitrogen in the input stream. As in *NCEES Handbook: Temperature*, the absolute temperature is

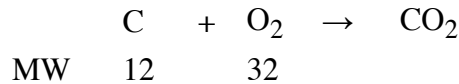
$$T = 40^\circ\text{C} + 273^\circ = 313\text{K}$$

$$\begin{aligned}\dot{m} &= \frac{p\dot{V}M}{RT} \\ &= \frac{(103 \text{ kPa})\left(1000 \frac{\text{Pa}}{\text{kPa}}\right)\left(0.3041 \frac{\text{m}^3}{\text{s}}\right)\left(28.016 \frac{\text{g}}{\text{mol}}\right)}{\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(313\text{K})} \\ &= 0.337 \text{ kg/s} \quad (0.34 \text{ kg/s})\end{aligned}$$

The answer is (D).

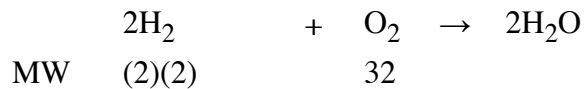
4.

The molecular weights can be found in *NCEES Handbook* table “Temperature-Independent Properties of Liquids and Gases (U.S. Units).” The combustion reaction should lead to  $\text{CO}_2$  and  $\text{H}_2\text{O}$  as the products. From table CERM24007, when properly balanced,



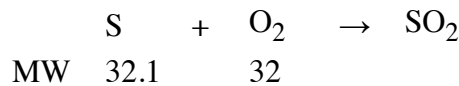
The mass of oxygen required per unit mass of carbon is

$$\frac{32}{12} = 2.67$$



The mass of oxygen required per unit mass of hydrogen is

$$\frac{32}{(2)(2)} = 8.0$$



The mass of oxygen required per unit mass of sulfur is

$$\frac{32}{32.1} = 1.0$$

Nitrogen does not burn.

The mass of oxygen required per unit mass of fuel is

$$\begin{aligned}(0.84)(2.67) + (0.153)(8) + (0.003)(1) \\ = 3.47 \text{ units of mass of O}_2/\text{unit mass fuel}\end{aligned}$$

From table CERM24006 (also *NCEES Handbook: Dry Atmospheric Air Composition*), air is 0.2315  $\text{O}_2$ /unit mass.

*Customary U.S. Solution*

The air required is

$$\frac{3.47}{0.2315} = 14.99 \quad (15 \text{ lbm air/lbm fuel})$$

The answer is (C).

*SI Solution*

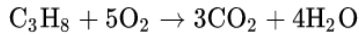
The air required is

$$\frac{3.47}{0.2315} = 14.99 \quad (15 \text{ kg air/kg fuel})$$

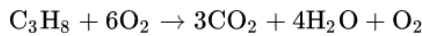
The answer is (C).

5.

The molecular weights can be found in *NCEES Handbook* table “Temperature-Independent Properties of Liquids and Gases (U.S. Units).” The combustion reaction should lead to  $\text{CO}_2$  and  $\text{H}_2\text{O}$  as the products. From table CERM24007, when properly balanced,

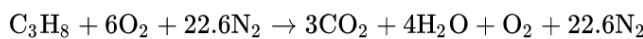


With 20% excess air, the oxygen volume is  $(1.2)(5) = 6$ .



From table CERM24006 (also *NCEES Handbook: Dry Atmospheric Air Composition*), there are 3.773 volumes of nitrogen for every volume of oxygen.

$$(6)(3.773) = 22.6$$



The percentage of carbon dioxide by weight in flue gas is

$$\begin{aligned} G_{\text{CO}_2} &= \frac{m_{\text{CO}_2}}{m_{\text{total}}} \\ &= \frac{B_{\text{CO}_2} (\text{MW}_{\text{CO}_2})}{\sum B_i (\text{MW}_i)} \\ &= \frac{(3)(44.011)}{(3)(44.011) + (4)(18.016) + 32 + (22.6)(28.016)} \\ &= 0.152 \quad (15\%) \end{aligned}$$

The answer is (C).

6.

*Customary U.S. Solution*

For every 1 lbm of coal burned, 0.8 lbm of coal is emitted as carbon. The carbon is balanced between CO and  $\text{CO}_2$ . Since 12/13 of the emitted carbon goes to  $\text{CO}_2$ , 0.74 lbm of carbon goes to forming  $\text{CO}_2$  for every 1 lbm of coal burned. As in *NCEES Handbook: Physical Properties of Liquids and Gases—Temperature-Independent Properties*, the molecular weight of carbon is 12 lbm/lbmol. The number of moles of  $\text{CO}_2$  emitted per 1 lbm of coal is

$$\begin{aligned} n_{\text{CO}_2} &= \frac{m_{\text{C}}}{M_{\text{C}}} = \frac{0.74 \text{ lbm}}{12 \frac{\text{lbm}}{\text{lbmol}}} \\ &= 0.062 \text{ lbmol CO}_2/\text{lbm coal} \end{aligned}$$

Since the nitrogen does not react, the nitrogen from the flow is from air. From the flue gas sampled, 80 parts of  $\text{N}_2$  are released for every 12 parts of  $\text{CO}_2$  released. The number of moles of  $\text{N}_2$  emitted per 1 lbm of coal is

$$\begin{aligned} n_{\text{N}_2} &= \frac{80}{12} n_{\text{CO}_2} = \left( \frac{80}{12} \right) \left( 0.062 \frac{\text{lbmol}}{\text{lbm}} \right) \\ &= 0.41 \text{ lbmol N}_2/\text{lbm coal} \end{aligned}$$

The mass of  $\text{N}_2$  is

$$\begin{aligned} m_{\text{N}_2} &= n_{\text{N}_2} M_{\text{N}_2} = \left( 0.41 \frac{\text{lbmol N}_2}{\text{lbm coal}} \right) \left( 28 \frac{\text{lbm}}{\text{lbmol}} \right) \\ &= 11.5 \text{ lbm N}_2/\text{lbm coal} \end{aligned}$$

As in *NCEES Handbook: Dry Atmospheric Air Composition*, the mass of oxygen in the air is the product of the molar flow of nitrogen, the ratio of O<sub>2</sub> and N<sub>2</sub> in the air, and the molecular weight of oxygen.

$$\begin{aligned} m_{\text{O}_2} &= \left(0.41 \frac{\text{lbmol N}_2}{\text{lbm coal}}\right) (0.2315) \left(32 \frac{\text{lbm}}{\text{lbmol}}\right) \\ &= 3 \text{ lbm O}_2/\text{lbm coal} \end{aligned}$$

The total air flow per 1 lbm of coal is

$$\begin{aligned} M_{\text{total}} &= m_{\text{N}_2} + m_{\text{O}_2} = 11.5 \frac{\text{lbm N}_2}{\text{lbm coal}} + 3 \frac{\text{lbm O}_2}{\text{lbm coal}} \\ &= 14.5 \text{ lbm air/lbm coal} \quad (15 \text{ lbm}) \end{aligned}$$

The answer is (B).

#### SI Solution

For every 1 kg of coal burned, 0.8 kg of coal is emitted as carbon. The carbon is balanced between CO and CO<sub>2</sub>. Since 12/13 of the emitted carbon goes to CO<sub>2</sub>, 0.74 kg of carbon goes to forming CO<sub>2</sub> for every 1 kg of coal burned. As in *NCEES Handbook: Physical Properties of Liquids and Gases—Temperature-Independent Properties*, the molecular weight of carbon is 12 kg/kmol. The number of moles of CO<sub>2</sub> emitted per 1 kg of coal is

$$\begin{aligned} n_{\text{CO}_2} &= \frac{m_{\text{C}}}{M_{\text{C}}} = \frac{0.74 \text{ kg}}{12 \frac{\text{kg}}{\text{kmol}}} \\ &= 0.062 \text{ kmol CO}_2/\text{kg coal} \end{aligned}$$

Since the nitrogen does not react, the nitrogen from the flow is from air. From the flue gas sampled, 80 parts of N<sub>2</sub> are released for every 12 parts released of CO<sub>2</sub>. The number of moles of N<sub>2</sub> is

$$\begin{aligned} n_{\text{N}_2} &= \frac{80}{12} n_{\text{CO}_2} = \left(\frac{80}{12}\right) \left(0.062 \frac{\text{kmol CO}_2}{\text{kg coal}}\right) \\ &= 0.41 \text{ kmol N}_2/\text{kg coal} \end{aligned}$$

The mass of N<sub>2</sub> is

$$\begin{aligned} m_{\text{N}_2} &= n_{\text{N}_2} M_{\text{N}_2} = \left(0.41 \frac{\text{kmol N}_2}{\text{kg coal}}\right) \left(28 \frac{\text{kg}}{\text{kmol}}\right) \\ &= 11.5 \text{ kg N}_2/\text{kg coal} \end{aligned}$$

As in *NCEES Handbook: Dry Atmospheric Air Composition*, the mass of oxygen in the air is the product of the molar flow of nitrogen, the ratio of O<sub>2</sub> and N<sub>2</sub> in the air, and the molecular weight of oxygen.

$$\begin{aligned} m_{\text{O}_2} &= \left(0.41 \frac{\text{kmol N}_2}{\text{kg coal}}\right) (0.2315) \left(32 \frac{\text{kg}}{\text{kmol}}\right) \\ &= 3 \text{ kg O}_2/\text{kg coal} \end{aligned}$$

The total air flow per kilogram of coal is

$$\begin{aligned} M_{\text{total}} &= m_{\text{N}_2} + m_{\text{O}_2} = 11.5 \frac{\text{kg N}_2}{\text{kg coal}} + 3 \frac{\text{kg O}_2}{\text{kg coal}} \\ &= 14.5 \text{ kg air/kg coal} \quad (15 \text{ kg}) \end{aligned}$$

The answer is (B).

7.

#### Customary U.S. Solution

step 1: Note the LHV for this fuel.

$$\text{LHV} = 12,957 \text{ Btu/lbm}$$

step 2: The gravimetric analysis of 1 lbm of coal is

carbon: 0.75 lbm

$$\begin{aligned}\text{free hydrogen: } G_{\text{H,total}} - \frac{G_{\text{O}}}{8} &= 0.05 - \frac{0.03}{8} \\ &= 0.0463\end{aligned}$$

The ratio of the molecular weight of water (18) to the molecular weight of hydrogen (2) is 9.

water: (9) (0.05 - 0.0463) = 0.0333

nitrogen: 0.02

step 3: Using stoichiometry and molecular weights from table CERM24008, the theoretical stack gases per lbm coal for 0.75 lbm of carbon are

$$\text{CO}_2 = (0.75) (3.667 \text{ lbm}) = 2.750 \text{ lbm}$$

$$\text{N}_2 = (0.75) (8.883 \text{ lbm}) = 6.662 \text{ lbm}$$

All products are calculated similarly (as the table summarizes). All values are per pound of fuel.

	CO <sub>2</sub>	N <sub>2</sub>	H <sub>2</sub> O
from C:	2.750 lbm	6.662 lbm	
from H <sub>2</sub> :		1.217 lbm	0.414 lbm
from H <sub>2</sub> O:			0.0333 lbm
from O <sub>2</sub> :	shows up in	CO <sub>2</sub> and H <sub>2</sub>	
from N <sub>2</sub> :		0.02 lbm	
total:	2.750 lbm	7.899 lbm	0.4473 lbm

step 4: Assume the combustion gases leave at 1000°F.

As in *NCEES Handbook*: Temperature,

$$\begin{aligned}T_{\text{ave}} &= \left(\frac{1}{2}\right) (60^\circ\text{F} + 1000^\circ\text{F}) = 530^\circ\text{F} \\ &= 530^\circ\text{F} + 460^\circ = 990^\circ\text{R}\end{aligned}$$

The specific heat values are given in table CERM24001 (also *NCEES Handbook* table “Temperature-Dependent Physical Properties of Gases at 14.7 psia (U.S. Units”).

$$c_{p,\text{CO}_2} = 0.251 \text{ Btu/lbm} \cdot ^\circ\text{F}$$

$$c_{p,\text{N}_2} = 0.255 \text{ Btu/lbm} \cdot ^\circ\text{F}$$

$$c_{p,\text{H}_2\text{O}} = 0.475 \text{ Btu/lbm} \cdot ^\circ\text{F}$$

The energy required to raise the combustion products (from 1 lbm of coal) 1°F is

$$\begin{aligned}&m_{\text{CO}_2} c_{p,\text{CO}_2} + m_{\text{N}_2} c_{p,\text{N}_2} + m_{\text{H}_2\text{O}} c_{p,\text{H}_2\text{O}} \\ &= (2.750 \text{ lbm}) \left( 0.251 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}} \right) \\ &\quad + (7.899 \text{ lbm}) \left( 0.255 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}} \right) \\ &\quad + (0.4473 \text{ lbm}) \left( 0.475 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}} \right) \\ &= 2.92 \text{ Btu}/^\circ\text{F}\end{aligned}$$

step 5: Assuming all combustion heat goes into the stack gases, the temperature is given by equation CERM24019.

$$\begin{aligned}
 T_{\max} &= T_i + \frac{\text{lower heat of combustion}}{\text{energy required}} \\
 &= 60^\circ\text{F} + \frac{12,957 \frac{\text{Btu}}{\text{lbm}}}{2.92 \frac{\text{Btu}}{\text{lbm}\cdot^\circ\text{F}}} \\
 &= 4497^\circ\text{F} \quad (4500^\circ\text{F})
 \end{aligned}$$

The answer is (C).

### SI Solution

*step 1:* Note the heating value of this fuel.

$$\text{LHV} = 30.14 \text{ MJ/kg}$$

Steps 2 and 3 are the same as for the customary U.S. solution except that all masses are in kg.

*step 4:* Assume the combustion gases leave at  $550^\circ\text{C}$ .

$$T_{\text{ave}} = \left(\frac{1}{2}\right)(16^\circ\text{C} + 550^\circ\text{C}) + 273^\circ = 556\text{K}$$

Specific heat values are given in table CERM24001 (also *NCEES Handbook* table “Temperature-Dependent Physical Properties of Gases at 0.1 MPa (SI Units)”). Using the footnote for SI units,

$$c_{p,\text{CO}_2} = 1.051 \text{ kJ/kg}\cdot\text{K}$$

$$c_{p,\text{N}_2} = 1.068 \text{ kJ/kg}\cdot\text{K}$$

$$c_{p,\text{H}_2\text{O}} = 1.989 \text{ kJ/kg}\cdot\text{K}$$

The energy required to raise the combustion products (from 1 kg of coal)  $1^\circ\text{C}$  is

$$\begin{aligned}
 &m_{\text{CO}_2} c_{p,\text{CO}_2} + m_{\text{N}_2} c_{p,\text{N}_2} + m_{\text{H}_2\text{O}} c_{p,\text{H}_2\text{O}} \\
 &= (2.750 \text{ kg}) \left(1.051 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right) \\
 &\quad + (7.899 \text{ kg}) \left(1.068 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right) \\
 &\quad + (0.4473 \text{ kg}) \left(1.989 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right) \\
 &= 12.22 \text{ kJ/K}
 \end{aligned}$$

*step 5:* Assuming all combustion heat goes into the stack gases, the temperature is given by equation CERM24019.

$$\begin{aligned}
 T_{\max} &= T_i + \frac{\text{lower heat of combustion}}{\text{energy required}} \\
 &= 16^\circ\text{C} + \frac{\left(30.14 \frac{\text{MJ}}{\text{kg}}\right) \left(1000 \frac{\text{kJ}}{\text{MJ}}\right)}{12.22 \frac{\text{kJ}}{\text{K}}} \\
 &= 2482^\circ\text{C} \quad (2500^\circ\text{C})
 \end{aligned}$$

The answer is (C).

[8.](#)

Assume the oxygen is in the form of moisture in the fuel. The available hydrogen is

$$G_{\text{H,free}} = G_{\text{H}} - \frac{G_{\text{O}}}{8} = 0.1131 - \frac{0.027}{8} = 0.1097$$

### Customary U.S. Solution

step 1: From the PPI manual, find the stoichiometric oxygen required per kilogram of fuel oil.

$$\begin{aligned}\text{C} \rightarrow \text{CO}_2: \text{O}_2 \text{ required} &= (0.8543) (2.667 \text{ lbm}) \\ &= 2.2784 \text{ lbm} \\ \text{H}_2 \rightarrow \text{H}_2\text{O}: \text{O}_2 \text{ required} &= (0.1097) (7.936 \text{ lbm}) \\ &= 0.8706 \text{ lbm} \\ \text{S} \rightarrow \text{SO}_2: \text{O}_2 \text{ required} &= (0.0034) (0.998 \text{ lbm}) \\ &= 0.0034 \text{ lbm}\end{aligned}$$

The amount of additional oxygen required per kilogram of fuel oil is

$$2.28 \text{ kg} + 0.905 \text{ kg} + 0.003 \text{ kg} - 0.027 \text{ kg} = 3.161 \text{ kg}$$

step 2: With 60% excess air, the excess oxygen per kilogram of fuel oil is

$$(0.6)(3.161 \text{ kg}) = 1.897 \text{ kg}$$

step 3: The theoretical nitrogen per pound of fuel based on the PPI manual (also the *NCEES Handbook* section titled “Dry Atmospheric Air Composition”) is

$$\left( 3.161 + 1.897 \right) \text{ kg O}_2 * \left( \frac{0.7685 \% \text{ N}_2}{0.2315 \% \text{ O}_2} \right) = 16.79 \text{ kg N}_2$$

Since mass of the fuel is conserved, the wet mass of flue gas produced is

$$1 \text{ kg of fuel} + 5.058 \text{ kg O}_2 + 16.79 \text{ kg N}_2 = 22.85 \text{ kg flue gas} \quad (23 \text{ kg})$$

The answer is (B).

[9.](#)

#### *Customary U.S. Solution*

step 1: Based on 15,395 lbm of coal burned producing 2816 lbm of ash containing 20.9% carbon by weight, the usable percentage of carbon per pound of fuel is

$$0.5145 - \frac{(2816 \text{ lbm})(0.209)}{15,395 \text{ lbm}} = 0.4763$$

step 2: Since moisture is reported separately, assume all of the oxygen and hydrogen are free. (This is not ordinarily the case.) From table CERM24008, find the stoichiometric oxygen required per pound of fuel.

$$\begin{aligned}\text{C} \rightarrow \text{CO}_2: \text{O}_2 \text{ required} &= (0.4763) (2.667 \text{ lbm}) \\ &= 1.2703 \text{ lbm} \\ \text{H}_2 \rightarrow \text{H}_2\text{O}: \text{O}_2 \text{ required} &= (0.0402) (7.936 \text{ lbm}) \\ &= 0.3190 \text{ lbm} \\ \text{S} \rightarrow \text{SO}_2: \text{O}_2 \text{ required} &= (0.0392) (0.998 \text{ lbm}) \\ &= 0.0391 \text{ lbm}\end{aligned}$$

The total amount of O<sub>2</sub> required per pound of fuel is

$$\begin{aligned}1.2703 \text{ lbm} + 0.3190 \text{ lbm} \\ + 0.0391 \text{ lbm} - 0.0728 \text{ lbm} = 1.5556 \text{ lbm}\end{aligned}$$

step 3: The theoretical air per pound of fuel based on table CERM24006 (also *NCEES Handbook: Dry Atmospheric Air Composition*) is

$$\frac{1.5556 \text{ lbm}}{0.2315} = 6.720 \text{ lbm air}$$

step 4: Ignoring fly ash, the theoretical dry products per pound of fuel are given from table CERM24008.



$$\begin{aligned}
 \text{CO}_2: (0.4763) (3.667 \text{ lbm}) &= 1.7466 \text{ lbm} \\
 \text{SO}_2: (0.0392) (1.998 \text{ lbm}) &= 0.0783 \text{ lbm} \\
 \text{N}_2: 0.0093 \text{ lbm} + (6.720 \text{ lbm}) (0.7685) &= \underline{5.1736 \text{ lbm}} \\
 \text{total} &= 6.999 \text{ lbm}
 \end{aligned}$$

step 5: The excess air per pound of fuel is

$$13.3 \text{ lbm} - 6.999 \text{ lbm} = 6.301 \text{ lbm}$$

step 6: The total air supplied per pound of fuel is

$$6.301 \text{ lbm} + 6.720 \text{ lbm} = 13.02 \text{ lbm} \quad (13 \text{ lbm})$$

The answer is (A).

*SI Solution*

step 1: Based on 6923 kg of coal burned producing 1267 kg of ash containing 20.9% carbon by weight, the usable percentage of carbon per kilogram of fuel is

$$0.5145 - \frac{(1267 \text{ kg}) (0.209)}{6923 \text{ kg}} = 0.4763$$

step 2: From table CERM24008, find the stoichiometric oxygen required per kilogram of fuel.

$$\begin{aligned}
 \text{C} \rightarrow \text{CO}_2: \text{O}_2 \text{ required} &= (0.4763) (2.667 \text{ kg}) \\
 &= 1.2703 \text{ kg} \\
 \text{H}_2 \rightarrow \text{H}_2\text{O}: \text{O}_2 \text{ required} &= (0.0402) (7.936 \text{ kg}) \\
 &= 0.3190 \text{ kg} \\
 \text{S} \rightarrow \text{SO}_2: \text{O}_2 \text{ required} &= (0.0392) (0.998 \text{ kg}) \\
 &= 0.0391 \text{ kg}
 \end{aligned}$$

The total amount of O<sub>2</sub> required per kilogram of fuel is

$$\begin{aligned}
 1.2703 \text{ kg} + 0.3190 \text{ kg} \\
 + 0.0391 \text{ kg} - 0.0728 \text{ kg} &= 1.5556 \text{ kg}
 \end{aligned}$$

step 3: The theoretical air per kilogram of fuel based on table CERM24006 (also *NCEES Handbook: Dry Atmospheric Air Composition*) is

$$\frac{1.5556 \text{ kg}}{0.2315} = 6.720 \text{ kg air}$$

step 4: Ignoring fly ash, the theoretical dry products per kilogram of fuel are given from table CERM24008.

$$\begin{aligned}
 \text{CO}_2: (0.4763) (3.667 \text{ kg}) &= 1.7466 \text{ kg} \\
 \text{SO}_2: (0.0392) (1.998 \text{ kg}) &= 0.0783 \text{ kg} \\
 \text{N}_2: 0.0093 \text{ kg} + (6.720 \text{ kg}) (0.7685) &= \underline{5.1736 \text{ kg}} \\
 \text{total} &= 6.999 \text{ kg}
 \end{aligned}$$

step 5: The excess air per kilogram of fuel is

$$13.3 \text{ kg} - 6.999 \text{ kg} = 6.301 \text{ kg}$$

step 6: The total air supplied per kilogram of fuel is

$$6.301 \text{ kg} + 6.720 \text{ kg} = 13.02 \text{ kg} \quad (13 \text{ kg})$$

The answer is (A).

Each 1 lbm of coal has 0.65 lbm of carbon. If 3% is lost, then 0.63 lbm of carbon make it to the effluent. The number of moles of carbon in the effluent is

$$n_C = \frac{m}{M} = \frac{0.63 \text{ lbm}}{12 \frac{\text{lbm}}{\text{lbmol}}} = 0.0525 \text{ lbmol C}$$

The carbon making it to the effluent appears as  $\text{CO}_2$ . Using the ratio of  $\text{N}_2$  to  $\text{CO}_2$  in the effluent, the number of moles of  $\text{N}_2$  is

$$n_{\text{N}_2} = \left( \frac{81.5}{9.5} \right) (0.0525 \text{ lbmol C}) = 0.45 \text{ lbmol N}_2$$

Using *NCEES Handbook: Dry Atmospheric Air Composition*, the number of moles of air is

$$n_{\text{O}_2} = \frac{0.45 \text{ lbmol N}_2}{3.76} = 0.12 \text{ lbmol O}_2$$

Using *NCEES Handbook: Physical Properties of Liquids and Gases—Temperature-Independent Properties*, the total mass of air into the system is

$$\begin{aligned} m_{\text{total}} &= n_{\text{N}_2} M_{\text{N}_2} + n_{\text{O}_2} M_{\text{O}_2} \\ &= (0.45 \text{ lbmol N}_2) \left( 28 \frac{\text{lbm}}{\text{lbmol}} \right) \\ &\quad + (0.12 \text{ lbmol O}_2) \left( 32 \frac{\text{lbm}}{\text{lbmol}} \right) \\ &= 16.44 \text{ lbm air} \end{aligned}$$

As in *NCEES Handbook: Material Balances With Reaction*, the percentage of excess air is

$$\begin{aligned} \% \text{ of excess air} &= \left( \frac{16.44 \text{ lbm} - 9.87 \text{ lbm}}{9.87 \text{ lbm}} \right) \times 100\% \\ &= 67\% \quad (70\%) \end{aligned}$$

The answer is (C).

[11.](#)

The amount of carbon leaving the flue per 1 lbm of coal is

$$m_C = (1 \text{ lbm}) (0.97) (0.6734) = 0.653 \text{ lbm C}$$

The molar percentage of C leaving as CO can be found from the percentages of CO and  $\text{CO}_2$  in the flue gas is

$$\% \text{C as CO} = \frac{y_{\text{CO}}}{y_{\text{CO}} + y_{\text{CO}_2}} = \frac{1.6}{1.6 + 15.5} \times 100\% = 9.4\%$$

Since CO and  $\text{CO}_2$  have the same amount of carbon, their mass ratios are the same leading to the same mass percent of carbon leaving as CO. The mass of carbon leaving as CO is

$$m_{\text{C as CO}} = (0.094) (0.653 \text{ lbm}) = 0.061 \text{ lbm C as CO}$$

The amount of CO leaving the flue per 1 lbm of coal is

$$n_{\text{CO}} = \frac{0.061 \text{ lbm}}{12 \frac{\text{lbm}}{\text{lbmol}}} = 0.00509 \text{ lbmol CO}$$

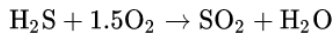
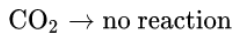
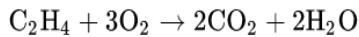
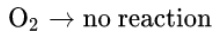
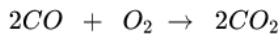
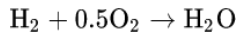
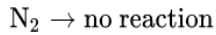
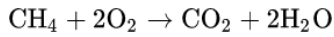
As in *NCEES Handbook: Standard Heat of Formation and Combustion*, the heat of combustion of CO is 121,700 Btu/lbmol, so the energy lost is

$$\begin{aligned}
 Q_{\text{lost}} &= (0.00509 \text{ lbmol CO}) \left( 121,700 \frac{\text{Btu}}{\text{lbmol}} \right) \\
 &= 619.4 \text{ Btu} \quad (600 \text{ Btu})
 \end{aligned}$$

The answer is (A).

[12.](#)

The reactions for the oxidation of the components of the natural gas are



Assume 100 moles of natural gas. To find the total moles of oxygen required, the composition can be multiplied by the stoichiometric coefficient for oxygen in the above reactions. Subtract the amount of oxygen in the natural gas.

$$\begin{aligned}
 n_{\text{O}_2} &= ((93 \text{ mol})(2) + (1.82 \text{ mol})(0.5) + (0.45 \text{ mol})(0.5) \\
 &\quad + (0.25 \text{ mol})(3) + (0.18 \text{ mol})(1.5)) - 0.35 \text{ mol} \\
 &= 187.81 \text{ mol O}_2
 \end{aligned}$$

Using *NCEES Handbook: Dry Atmospheric Air Composition*, the theoretical air requirements are most nearly

$$\begin{aligned}
 n_{\text{air}} &= \frac{\left( \frac{1 \text{ mol air}}{0.209390 \text{ mol O}_2} \right) (187.81 \text{ mol O}_2)}{100 \text{ mol gas}} \\
 &= 8.969 \frac{\text{mol air}}{\text{mol gas}} \\
 &= 8.969 \text{ ft}^3 \text{ air/ft}^3 \text{ fuel} \quad (9 \text{ ft}^3 \text{ air/ft}^3 \text{ fuel})
 \end{aligned}$$

The answer is (C).

[13.](#)

*Customary U.S. Solution*

*step 1:* The incoming reactants on a per-pound basis are

0.07 lbm ash  
 0.05 lbm hydrogen  
 0.05 lbm oxygen  
 0.83 lbm carbon

This is an ultimate analysis. Assume that only the hydrogen that is not locked up with oxygen in the form of water is combustible. From equation CERM24015, the available hydrogen is

$$\begin{aligned}
 G_{\text{H,available}} &= G_{\text{H,total}} - \frac{G_{\text{O}}}{8} = 0.05 \text{ lbm} - \frac{0.05 \text{ lbm}}{8} \\
 &= 0.04375 \text{ lbm}
 \end{aligned}$$

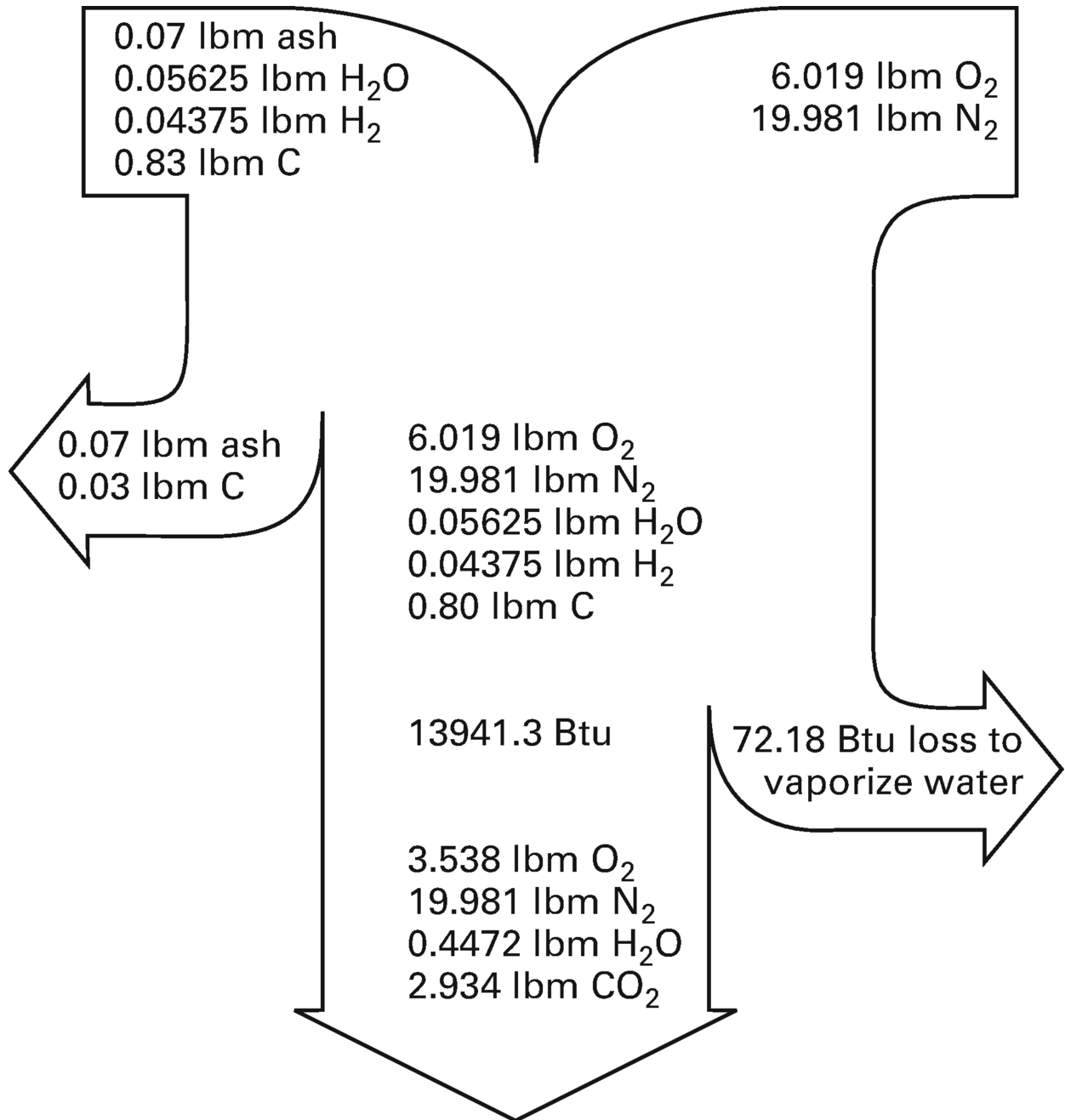
The mass of water produced is the hydrogen mass plus eight times as much oxygen. The locked hydrogen is

$$0.05 \text{ lbm} - 0.04375 \text{ lbm} = 0.00625 \text{ lbm}$$

$$\begin{aligned}
 \text{lbm of moisture} &= G_H + G_O = G_H + 8G_C \\
 &= 0.00625 \text{ lbm} + (8)(0.00625 \text{ lbm}) \\
 &= 0.05625 \text{ lbm}
 \end{aligned}$$

The air is 23.15% oxygen by weight (see table CERM24006 and *NCEES Handbook: Dry Atmospheric Air Composition*), so other reactants for 26 lbm of air are

$$\begin{aligned}
 (0.2315)(26 \text{ lbm}) &= 6.019 \text{ lbm O}_2 \\
 (0.7685)(26 \text{ lbm}) &= 19.981 \text{ lbm N}_2
 \end{aligned}$$



*step 2:* Ash pit material losses are 10%, or 0.1 lbm, which includes all of the ash.

0.07 lbm ash (noncombustible matter)  
0.03 lbm unburned carbon

*step 3:* Determine what remains.

6.019 lbm oxygen  
19.981 lbm nitrogen  
0.05625 lbm water  
0.04375 lbm hydrogen  
0.80 lbm carbon

step 4: Determine the energy loss in vaporizing the moisture.

$$q = (\text{moisture}) (h_g - h_f)$$

From appendix MERM24C (also *NCEES Handbook: Superheated Steam* (U.S. Customary Units)),  $h_g$  at 550°F and 14.7 psia is 1311.4 Btu/lbm.

From appendix MERM24A (also *NCEES Handbook: Properties of Saturated Steam* (U.S. Customary Units)),  $h_f$  at 60°F is 28.08 Btu/lbm.

$$\begin{aligned} q &= (0.05625 \text{ lbm}) \left( 1311.4 \frac{\text{Btu}}{\text{lbm}} - 28.08 \frac{\text{Btu}}{\text{lbm}} \right) \\ &= 72.19 \text{ Btu} \end{aligned}$$

step 5: Calculate the heating value of the remaining fuel components using appendix CERM24A (also *NCEES Handbook: Standard Heat of Formation and Combustion*).

$$\begin{aligned} \text{HV}_C &= (0.80 \text{ lbm}) \left( 14,093 \frac{\text{Btu}}{\text{lbm}} \right) = 11,274.4 \text{ Btu} \\ \text{HV}_H &= (0.04375 \text{ lbm}) \left( 60,958 \frac{\text{Btu}}{\text{lbm}} \right) = 2666.9 \text{ Btu} \end{aligned}$$

The heating value after the coal moisture is evaporated (i.e., the as-delivered heating value) is

$$11,274.4 \text{ Btu} + 2666.9 \text{ Btu} - 72.19 \text{ Btu} = 13,869 \text{ Btu}$$

step 6: Using table CERM24008, determine the combustion products.

$$\begin{aligned} \text{oxygen required by carbon} &= (0.80) (2.667 \text{ lbm}) \\ &= 2.134 \text{ lbm} \\ \text{oxygen required by hydrogen} &= (0.04375) (7.936 \text{ lbm}) \\ &= 0.3472 \text{ lbm} \\ \text{carbon dioxide produced by carbon} &= (0.8) (3.667 \text{ lbm}) \\ &= 2.934 \text{ lbm} \\ \text{water produced by hydrogen} &= (0.04375) (8.936 \text{ lbm}) \\ &= 0.3910 \text{ lbm} \end{aligned}$$

The remaining oxygen is

$$6.019 \text{ lbm} - 2.134 \text{ lbm} - 0.3472 \text{ lbm} = 3.538 \text{ lbm}$$

step 7: The gaseous products must be heated from 70°F to 550°F. The average temperature is

$$\left( \frac{1}{2} \right) (70^\circ\text{F} + 550^\circ\text{F}) + 460^\circ = 770^\circ\text{R}$$

From table CERM24001 (also *NCEES Handbook* table “Temperature-Dependent Physical Properties of Gases at 14.7 psia (U.S. Units)”), the specific heat of gaseous products, omitting water, is

gas	$\frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{R}}$
oxygen	0.228
nitrogen	0.252
carbon dioxide	0.225

$$\begin{aligned}
 Q_{\text{heating}} &= \left( \begin{aligned} &(3.538 \text{ lbm}) \left( 0.228 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{R}} \right) \\ &+ (19.981 \text{ lbm}) \left( 0.252 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{R}} \right) \\ &+ (2.934 \text{ lbm}) \left( 0.225 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{R}} \right) \end{aligned} \right) \\
 &\quad \times (550^\circ\text{F} - 70^\circ\text{F}) \\
 &= 3121 \text{ Btu}
 \end{aligned}$$

Find the enthalpy of steam at 550°F and 1 atm using *NCEES Handbook* table “Superheated Steam (U.S. Units).” Find the enthalpy of steam at 70°F and 1 atm using *NCEES Handbook* table “Saturated Steam (U.S. Units)—Temperature Table”. So,

$$\begin{aligned}
 Q_{\text{steam}} &= m (h_{550^\circ\text{F}} - h_{70^\circ\text{F}}) \\
 &= (0.3910 \text{ lbm}) \left( 1312 \frac{\text{Btu}}{\text{lbm}} - 1092.1 \frac{\text{Btu}}{\text{lbm}} \right) \\
 &= 86 \text{ Btu}
 \end{aligned}$$

The total heat is

$$\begin{aligned}
 Q_{\text{total}} &= Q_{\text{heating}} + Q_{\text{steam}} = 3121 \text{ Btu} + 86 \text{ Btu} \\
 &= 3207 \text{ Btu}
 \end{aligned}$$

*step 8:* The percentage loss based on the coal’s as-delivered heating value is

$$\frac{3207.3 \text{ Btu} + 72.19 \text{ Btu}}{13,869 \text{ Btu}} = 0.236 \quad (24\%)$$

*The answer is (B).*

*SI Solution*

Steps 1 through 3 are the same as for the customary U.S. solution except that everything is based on kg.

*step 4:* Determine the energy loss in the vaporizing moisture.

$$q = (\text{moisture}) (h_g - h_f)$$

From appendix MERM24P (also *NCEES Handbook: Superheated Steam (SI Units)*),  $h_g$  at 290°C and 101.3 kPa is 3054.5 kJ/kg.

$h_f$  at 15.6°C from appendix MERM24N (also *NCEES Handbook: Saturated Steam (SI Units)*) is 65.49 kJ/kg.

$$\begin{aligned}
 q &= (0.05625 \text{ kg}) \left( 3054.5 \frac{\text{kJ}}{\text{kg}} - 65.49 \frac{\text{kJ}}{\text{kg}} \right) \\
 &= 168.1 \text{ kJ}
 \end{aligned}$$

*step 5:* Calculate the heating value of the remaining fuel components using appendix CERM24A (also *NCEES Handbook: Standard Heat of Formation and Combustion*) and the table footnote.

$$\begin{aligned}
 \text{HV}_C &= (0.80 \text{ kg}) \left( 14,093 \frac{\text{Btu}}{\text{lbm}} \right) \left( 2.326 \frac{\frac{\text{kJ}}{\text{kg}}}{\frac{\text{Btu}}{\text{lbm}}} \right) \\
 &= 26,224 \text{ kJ} \\
 \text{HV}_H &= (0.04375 \text{ kg}) \left( 60,958 \frac{\text{Btu}}{\text{lbm}} \right) \left( 2.326 \frac{\frac{\text{kJ}}{\text{kg}}}{\frac{\text{Btu}}{\text{lbm}}} \right) \\
 &= 6,203 \text{ kJ}
 \end{aligned}$$

The heating value after the coal moisture is evaporated is

$$26\,224\text{ kJ} + 6203\text{ kJ} - 168.1\text{ kJ} = 32\,259\text{ kJ}$$

*step 6:* This step is the same as for the customary U.S. solution except that all quantities are in kg.

*step 7:* The gaseous products must be heated from 21°C to 290°C. The average temperature is

$$\left(\frac{1}{2}\right)(21^\circ\text{C} + 290^\circ\text{C}) + 273^\circ = 428.5\text{K}$$

$$(428.5\text{K})\left(1.8\frac{^\circ\text{R}}{\text{K}}\right) = 771^\circ\text{R}$$

From table CERM24001 (also *NCEES Handbook* table “Temperature-Dependent Physical Properties of Gases at 14.7 psia (U.S. Units)”), the specific heat of gaseous products is calculated using the table footnote, and omitting water.

gas	$\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$
oxygen	0.955
nitrogen	1.055
carbon dioxide	0.942

$$Q_{\text{heating}} = \left( \begin{aligned} &(3.538\text{ kg})\left(0.955\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right) \\ &+ (19.981\text{ kg})\left(1.055\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right) \\ &+ (2.934\text{ kg})\left(0.942\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right) \end{aligned} \right) \times (290^\circ\text{C} - 21^\circ\text{C})$$

$$= 7322.8\text{ kJ}$$

Find the enthalpy of steam at 290°C and 1 atm using *NCEES Handbook* table “Superheated Steam (U.S. Units).” Find the enthalpy of steam at 21°C and 1 atm using *NCEES Handbook* table “Saturated Steam (SI Units).” So,

$$Q_{\text{steam}} = m(h_{550^\circ\text{F}} - h_{70^\circ\text{F}})$$

$$= (0.3910\text{ kg})\left(3054.3\frac{\text{kJ}}{\text{kg}} - 2539.9\frac{\text{kJ}}{\text{kg}}\right)$$

$$= 201.1\text{ kJ}$$

The total heat is

$$Q_{\text{total}} = Q_{\text{heating}} + Q_{\text{steam}} = 7322.8\text{ kJ} + 201.1\text{ kJ}$$

$$= 7523.9\text{ kJ}$$

*step 8:* The percentage loss is

$$\frac{7523.9\text{ kJ} + 168.1\text{ kJ}}{32\,259\text{ kJ}} = 0.238 \quad (24\%)$$

The answer is (B).

[14.](#)

As in *NCEES Handbook* table “Temperature- Independent Properties of Liquids and Gases (U.S. Units),” silicon in ash is  $\text{SiO}_2$  with a molecular weight of

$$28.09\frac{\text{lbm}}{\text{lbmol}} + (2)\left(16\frac{\text{lbm}}{\text{lbmol}}\right) = 60.09\text{ lbm/lbmol}$$

The oxygen used with 6.1% by mass silicon is

$$\left( \frac{(2)(16 \text{ lbm})}{28.09 \text{ lbm}} \right) \left( 0.061 \frac{\text{lbm}}{\text{lbm coal}} \right) \\ = 0.0695 \text{ lbm/lbm coal}$$

Silicon ash produced per lbm of coal is

$$0.061 \frac{\text{lbm}}{\text{lbm coal}} + 0.0695 \frac{\text{lbm}}{\text{lbm coal}} \\ = 0.1305 \text{ lbm/lbm coal}$$

Silicon ash produced per hour is

$$\left( 0.1305 \frac{\text{lbm}}{\text{lbm coal}} \right) \left( 15,300 \frac{\text{lbm coal}}{\text{hr}} \right) \\ = 1996.7 \text{ lbm/hr}$$

The silicon in 410 lbm/hr refuse is

$$\left( 410 \frac{\text{lbm}}{\text{hr}} \right) (1 - 0.3) = 287 \text{ lbm/hr}$$

The emission rate is

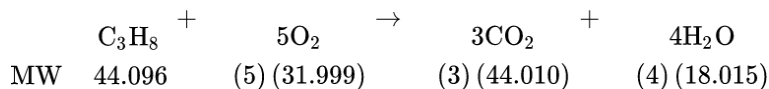
$$1996.7 \frac{\text{lbm}}{\text{hr}} - 287 \frac{\text{lbm}}{\text{hr}} \\ = 1709.7 \text{ lbm/hr} \quad (1700 \text{ lbm/hr})$$

The answer is (D).

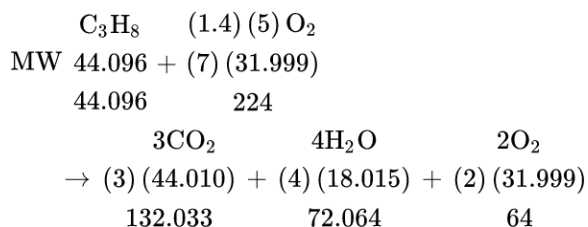
[15.](#)

*Customary U.S. Solution*

The stoichiometric reaction for propane is given in table CERM24007 (also *NCEES Handbook* table “Temperature-Independent Properties of Liquids and Gases (U.S. Units”).



With 40% excess O<sub>2</sub> by weight,



The excess oxygen is

$$(2)(32) = 64 \text{ lbm/lbmol C}_3\text{H}_8$$

The mass ratio of nitrogen to oxygen is

$$\frac{G_N}{G_O} = \left( \frac{B_N}{M_N} \right) \left( \frac{M_O}{B_O} \right) \\ = \left( \frac{0.40}{28 \frac{\text{lbm}}{\text{lbmol}}} \right) \left( \frac{32 \frac{\text{lbm}}{\text{lbmol}}}{0.60} \right) \\ = 0.762$$

The nitrogen accompanying the oxygen is



$$(7)(32)(0.762) = 170.7 \text{ lbm}$$

The mass balance per mole of propane is

$$\begin{array}{rcl} \text{C}_3\text{H}_8 + \text{O}_2 + \text{N}_2 & \rightarrow & \text{CO}_2 + \text{H}_2\text{O} + \text{O}_2 + \text{N}_2 \\ \text{mass per} & 44.096 + 224 + 170.7 \rightarrow 132.033 + 72.064 + 64 + & \\ \text{mole} & 170.7 & \end{array}$$

Standard conditions are 60°F and 1 atm. The propane density is given by equation MERM24050 (also *NCEES Handbook*: Ideal Gas Law).

$$\rho = \frac{pM}{RT}$$

As in *NCEES Handbook*: Temperature, the absolute temperature,  $T$ , is

$$60^\circ\text{F} + 460^\circ = 520^\circ\text{R}$$

$$\rho = \frac{\left(14.7 \frac{\text{lbf}}{\text{in}^2}\right) \left(12 \frac{\text{in}}{\text{ft}}\right)^2 \left(44.097 \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545.35 \frac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot^\circ\text{R}}\right) (520^\circ\text{R})} = 0.1162 \text{ lbm/ft}^3$$

The mass flow rate of propane is

$$\left(250 \frac{\text{ft}^3}{\text{min}}\right) \left(0.1162 \frac{\text{lbm}}{\text{ft}^3}\right) = 29.05 \text{ lbm/min}$$

Scaling the other mass balance factors down by

$$\frac{29.05 \frac{\text{lbm}}{\text{min}}}{44.097 \frac{\text{lbm}}{\text{lbmol}}} = 0.6588 \text{ lbmol/min}$$

$$\begin{array}{rcl} \text{C}_3\text{H}_8 + \text{O}_2 + \text{N}_2 & \rightarrow & \text{CO}_2 + \text{H}_2\text{O} + \text{O}_2 + \text{N}_2 \\ \frac{\text{lbm}}{\text{min}} & 29.05 + 147.57 + 112.5 \rightarrow 86.98 + 47.48 + 42.16 + 112.5 & \end{array}$$

The oxygen flow rate is 147.57 lbm/min.

From table CERM24007 (also *NCEES Handbook*: Ideal Gas Law), the specific volumes of the reactants are given by

$$\begin{aligned} v_{\text{C}_3\text{H}_8} &= \frac{RT}{pM} = \frac{\left(1545.35 \frac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot^\circ\text{R}}\right) (540^\circ\text{R})}{\left(14.7 \frac{\text{lbf}}{\text{in}^2}\right) \left(12 \frac{\text{in}}{\text{ft}}\right)^2 \left(44.097 \frac{\text{lbm}}{\text{lbmol}}\right)} \\ &= 8.939 \text{ ft}^3/\text{lbm} \\ v_{\text{O}_2} &= \frac{RT}{pM} = \frac{\left(1545.35 \frac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot^\circ\text{R}}\right) (540^\circ\text{R})}{\left(14.7 \frac{\text{lbf}}{\text{in}^2}\right) \left(12 \frac{\text{in}}{\text{ft}}\right)^2 \left(32 \frac{\text{lbm}}{\text{lbmol}}\right)} \\ &= 12.319 \text{ ft}^3/\text{lbm} \\ v_{\text{N}_2} &= \frac{RT}{pM} = \frac{\left(1545.35 \frac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot^\circ\text{R}}\right) (540^\circ\text{R})}{\left(14.7 \frac{\text{lbf}}{\text{in}^2}\right) \left(12 \frac{\text{in}}{\text{ft}}\right)^2 \left(28 \frac{\text{lbm}}{\text{lbmol}}\right)} \\ &= 14.071 \text{ ft}^3/\text{lbm} \end{aligned}$$

The total incoming volume is

$$\begin{aligned}\dot{V} &= \left(29.05 \frac{\text{lbm}}{\text{min}}\right) \left(8.939 \frac{\text{ft}^3}{\text{lbm}}\right) \\ &\quad + \left(147.57 \frac{\text{lbm}}{\text{min}}\right) \left(12.319 \frac{\text{ft}^3}{\text{lbm}}\right) \\ &\quad + \left(112.5 \frac{\text{lbm}}{\text{min}}\right) \left(14.071 \frac{\text{ft}^3}{\text{lbm}}\right) \\ &= 3660 \text{ ft}^3/\text{min}\end{aligned}$$

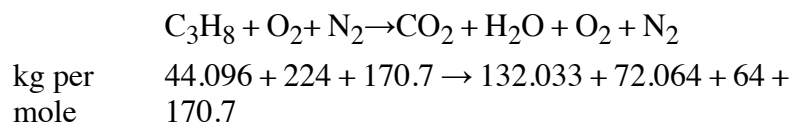
Since the velocity must be kept below 400 ft/min, the minimum area of inlet pipe is

$$A_{\text{inlet}} = \frac{\dot{V}}{v} = \frac{3660 \frac{\text{ft}^3}{\text{min}}}{400 \frac{\text{ft}}{\text{min}}} = 9.15 \text{ ft}^2 \quad (9 \text{ ft}^2)$$

The answer is (A).

### SI Solution

Following the procedure for the customary U.S. solution, the mass balance per mole of propane is



Standard conditions are 16°C and 101.3 kPa. The propane density is given by equation MERM24050 (also *NCEES Handbook*: Ideal Gas Law).

$$\rho = \frac{pM}{RT}$$

As in *NCEES Handbook*: Temperature, the absolute temperature is

$$T = 16^\circ\text{C} + 273^\circ = 289\text{K}$$

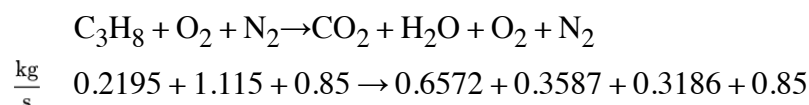
$$\rho = \frac{(101\,300 \text{ Pa}) \left(44.097 \frac{\text{g}}{\text{mol}}\right)}{\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right) (289\text{K})} = 1.86 \text{ kg/m}^3$$

The mass flow rate of propane is

$$\frac{\left(118 \frac{\text{L}}{\text{s}}\right) \left(1.86 \frac{\text{kg}}{\text{m}^3}\right)}{1000 \frac{\text{L}}{\text{m}^3}} = 0.2195 \text{ kg/s}$$

Scale the other mass balance factors down.

$$\frac{0.2195 \frac{\text{kg}}{\text{s}}}{44.097 \frac{\text{kg}}{\text{kmol}}} = 0.004978 \text{ kmol/s}$$



The oxygen flow rate is 1.115 kg/s.

From table MERM24007 (also *NCEES Handbook: Ideal Gas Law*), the specific volumes of the reactants are given by equation MERM24050.

$$\begin{aligned}
 v_{\text{C}_3\text{H}_8} &= \frac{RT}{pM} = \frac{\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(300\text{K})}{(101\,300\text{ Pa})\left(44.097 \frac{\text{g}}{\text{mol}}\right)} \\
 &= 0.56 \text{ m}^3/\text{kg} \\
 v_{\text{O}_2} &= \frac{RT}{pM} = \frac{\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(300\text{K})}{(101\,300\text{ Pa})\left(32 \frac{\text{g}}{\text{mol}}\right)} \\
 &= 0.7717 \text{ m}^3/\text{kg} \\
 v_{\text{N}_2} &= \frac{RT}{pM} = \frac{\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(300\text{K})}{(101\,300\text{ Pa})\left(28 \frac{\text{g}}{\text{mol}}\right)} \\
 &= 0.8815 \text{ m}^3/\text{kg}
 \end{aligned}$$

The total incoming volume,  $\dot{v}$ , is

$$\begin{aligned}
 \dot{V} &= \left(0.2195 \frac{\text{kg}}{\text{s}}\right) \left(0.5600 \frac{\text{m}^3}{\text{kg}}\right) \\
 &\quad + \left(1.115 \frac{\text{kg}}{\text{s}}\right) \left(0.7717 \frac{\text{m}^3}{\text{kg}}\right) \\
 &\quad + \left(0.85 \frac{\text{kg}}{\text{s}}\right) \left(0.8815 \frac{\text{m}^3}{\text{kg}}\right) \\
 &= 1.73 \text{ m}^3/\text{s}
 \end{aligned}$$

Since the velocity for the reactants must be kept below 2 m/s, the minimum area of inlet pipe is

$$A_{\text{inlet}} = \frac{\dot{V}}{v} = \frac{1.73 \frac{\text{m}^3}{\text{s}}}{2 \frac{\text{m}}{\text{s}}} = 0.866 \text{ m}^2 \quad (0.9 \text{ m}^2)$$

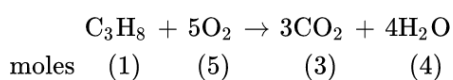
The answer is (A).

[16.](#)

### Customary U.S. Solution

Since atmospheric air is not used, the nitrogen and oxygen can be varied independently. Furthermore, since enthalpy increase information is not given for oxygen, a 0% excess of oxygen can be assumed.

The stoichiometric equation for the ideal combustion reaction of propane with only stoichiometric oxygen and forming only carbon dioxide and water is



Using the equation for standard heats of formations found in the *NCEES Handbook*: section titled “Heat of Reaction,” subtract the reactants’ standard heat of formation enthalpies from the products’ standard heat of formation enthalpies to calculate the heat of reaction. The enthalpy of formation of oxygen is zero since it is an element in its natural state. The heat of reaction (heat of combustion) is

$$\begin{aligned}
& n_{\text{CO}_2}(\Delta H_f)_{\text{CO}_2} + n_{\text{H}_2\text{O}}(\Delta H_f)_{\text{H}_2\text{O}} \\
& - n_{\text{C}_3\text{H}_8}(\Delta H_f)_{\text{C}_3\text{H}_8} - n_{\text{O}_2}(\Delta H_f)_{\text{O}_2} \\
& = \left(3 \frac{\text{lbmol}}{\text{lbmol}}\right) \left(-169,300 \frac{\text{Btu}}{\text{lbmol}}\right) \\
& + \left(4 \frac{\text{lbmol}}{\text{lbmol}}\right) \left(-104,040 \frac{\text{Btu}}{\text{lbmol}}\right) \\
& - \left(1 \frac{\text{lbmol}}{\text{lbmol}}\right) \left(28,800 \frac{\text{Btu}}{\text{lbmol}}\right) \\
& - \left(5 \frac{\text{lbmol}}{\text{lbmol}}\right) \left(0 \frac{\text{Btu}}{\text{lbmol}}\right) \\
& = -952,860 \text{ Btu/lbmol of propane}
\end{aligned}$$

The negative sign indicates an exothermic reaction.

Let  $x$  be the number of moles of nitrogen per mole of propane. Use the nitrogen to cool the combustion. The heat of reaction will increase the enthalpy of products from the standard reference temperature to  $3600^\circ\text{R}$ .

$$\begin{aligned}
952,860 \frac{\text{Btu}}{\text{lbmol}} & = \left(3 \frac{\text{lbmol}}{\text{lbmol}}\right) \left(39,791 \frac{\text{Btu}}{\text{lbmol}}\right) \\
& + \left(4 \frac{\text{lbmol}}{\text{lbmol}}\right) \left(31,658 \frac{\text{Btu}}{\text{lbmol}}\right) \\
& + x \left(24,471 \frac{\text{Btu}}{\text{lbmol}}\right) \\
x & = 28.89 \text{ lbmol/lbmol propane}
\end{aligned}$$

The mass of nitrogen per pound-mole of propane is

$$\begin{aligned}
m_{\text{N}_2} & = \left(28.89 \frac{\text{lbmol}}{\text{lbmol propane}}\right) \left(28.016 \frac{\text{lbm}}{\text{lbmol}}\right) \\
& = 809.4 \text{ lbm/lbmol} \quad (810 \text{ lbm/lbmol})
\end{aligned}$$

The mass of oxygen per pound-mole of propane is

$$\begin{aligned}
m_{\text{O}_2} & = \left(5 \frac{\text{lbmol}}{\text{lbmol}}\right) \left(32 \frac{\text{lbm}}{\text{lbmol}}\right) \\
& = 160 \text{ lbm/lbmol}
\end{aligned}$$

The answer is (B).

### SI Solution

From the customary U.S. solution, the heat of reaction is

$$\begin{aligned}
& n_{\text{CO}_2}(\Delta H_f)_{\text{CO}_2} + n_{\text{H}_2\text{O}}(\Delta H_f)_{\text{H}_2\text{O}} \\
& - n_{\text{C}_3\text{H}_8}(\Delta H_f)_{\text{C}_3\text{H}_8} - n_{\text{O}_2}(\Delta H_f)_{\text{O}_2} \\
& = \left(3 \frac{\text{kmol}}{\text{kmol}}\right) \left(-393.8 \frac{\text{GJ}}{\text{kmol}}\right) \\
& + \left(4 \frac{\text{kmol}}{\text{kmol}}\right) \left(-242 \frac{\text{GJ}}{\text{kmol}}\right) \\
& + \left(1 \frac{\text{kmol}}{\text{kmol}}\right) \left(-67.0 \frac{\text{GJ}}{\text{kmol}}\right) \\
& - \left(5 \frac{\text{kmol}}{\text{kmol}}\right) \left(0 \frac{\text{GJ}}{\text{kmol}}\right) \\
& = -2216.4 \text{ GJ/kmol propane}
\end{aligned}$$

The negative sign indicates an exothermic reaction.

Let  $x$  be the number of moles of nitrogen per mole of propane. Use the nitrogen to cool the combustion. The heat of reaction will increase the enthalpy of products from the standard reference temperature to 1980°C.

$$\begin{aligned}
 2216.4 \frac{\text{GJ}}{\text{mol}} &= \left( 3 \frac{\text{kmol}}{\text{kmol}} \right) \left( 92.6 \frac{\text{GJ}}{\text{kmol}} \right) \\
 &\quad + \left( 4 \frac{\text{kmol}}{\text{kmol}} \right) \left( 73.6 \frac{\text{GJ}}{\text{kmol}} \right) \\
 &\quad + x \left( 56.9 \frac{\text{GJ}}{\text{kmol}} \right) \\
 x &= 28.90 \text{ kmol/kmol propane}
 \end{aligned}$$

The mass of nitrogen per mole of propane is

$$\begin{aligned}
 m_{\text{N}_2} &= \left( 28.90 \frac{\text{kmol}}{\text{kmol}} \right) \left( 28.016 \frac{\text{kg}}{\text{kmol}} \right) \\
 &= 809.7 \text{ kg/kmol} \quad (810 \text{ kg/kmol})
 \end{aligned}$$

The mass of oxygen per kmol of propane is

$$m_{\text{O}_2} = \left( 5 \frac{\text{kmol}}{\text{kmol}} \right) \left( 32 \frac{\text{kg}}{\text{kmol}} \right) = 160 \text{ kg/kmol}$$

The answer is (B).

[17.](#)

The heat rate,  $Q$ , required to generate the steam is found from the generation rate of steam,  $\dot{m}$ , the enthalpy of the saturated vapor,  $h_g$ , and the enthalpy of the incoming saturated feedwater,  $h_f$ . From appendix MERM24B (also *NCEES Handbook: Properties of Saturated Steam (U.S. Customary Units)*), for an absolute pressure of 200 lbf/in<sup>2</sup>,  $h_g$  is 1198.8 Btu/lbm. From appendix MERM24A, for a temperature of 160°F,  $h_f$  is 128.0 Btu/lbm.

$$\begin{aligned}
 Q &= \dot{m} (h_g - h_f) \\
 &= \left( 20,070 \frac{\text{lbm}}{\text{hr}} \right) \left( 1198.8 \frac{\text{Btu}}{\text{lbm}} - 128.0 \frac{\text{Btu}}{\text{lbm}} \right) \\
 &= 21.5 \times 10^6 \text{ Btu/hr}
 \end{aligned}$$

The lower heating value of the fuel, LHV, is

$$\text{LHV} = \frac{Q}{\dot{m}_{\text{fuel}}} = \frac{21.5 \times 10^6 \frac{\text{Btu}}{\text{hr}}}{5000 \frac{\text{lbm}}{\text{hr}}} = 4300 \text{ Btu/lbm}$$

The higher heating value, HHV, includes the heat of vaporization (same as the heat of condensation) of the water in the fuel and generated by the combustion of the fuel. The mass of water in the combustion products produced per point of fuel is

$$m_{\text{water}} = \frac{2000 \frac{\text{lbm water}}{\text{hr}}}{5000 \frac{\text{lbm fuel}}{\text{hr}}} = 0.4 \text{ lbm water/lbm fuel}$$

From appendix MERM24B (also *NCEES Handbook: Properties of Saturated Steam (U.S. Customary Units)*), for a partial pressure of 4 lbf/in<sup>2</sup>, the enthalpy of vaporization,  $h_{fg}$ , is 1006.0 Btu/lbm. From equation CERM24014 (also *NCEES Handbook: Combustion Reactions*), the higher heating value is

$$\begin{aligned}
 \text{HHV} &= \text{LHV} + m_{\text{water}} h_{fg} \\
 &= 4300 \frac{\text{Btu}}{\text{lbm}} + \left( 0.4 \frac{\text{lbm}}{\text{lbm}} \right) \left( 1006.0 \frac{\text{Btu}}{\text{lbm}} \right) \\
 &= 4702.4 \text{ Btu/lbm} \quad (4700 \text{ Btu/lbm})
 \end{aligned}$$

The answer is (B).