

PRACTICE PAPER — SET 4

NATIONAL CERTIFICATION EXAMINATION FOR ENERGY MANAGERS & ENERGY AUDITORS

PAPER – 2: ENERGY EFFICIENCY IN THERMAL UTILITIES

Question Code: 4P2CEM — SOLUTIONS & MODEL ANSWERS

Duration: 3 HRS Max. Marks: 150

General instructions:

- Please check that this question paper contains 64 questions
- The question paper is divided into three sections
- All questions in all three sections are compulsory
- All parts of a question should be answered at one place
- Use of a non-programmable scientific calculator is permitted

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Section – I: OBJECTIVE TYPE

Marks: 50 x 1 = 50

(i) Answer all 50 questions

(ii) Each question carries one mark

1. A forge buys 3,000 t/yr of furnace oil (GCV 10,500 kcal/kg ($\approx$ 43,961 kJ/kg) on dry oil) at ₹ 48,000 per tonne. Tank-bottom sampling shows 3% free water on delivery, against the 1% maximum in the standard. Taking the latent heat of the water as 584 kcal/kg ($\approx$ 2,445 kJ/kg), the annual value of the heat lost compared with water-free oil is about:

[4P2CEM001]

- a) ₹ 28.8 lakh
- b) ₹ 30.4 lakh
- c) ₹ 43.2 lakh
- d) ₹ 45.6 lakh**

Correct answer: (d) ₹ 45.6 lakh.

Given: oil 3,000 t/yr; water 3% by mass; GCV 10,500 kcal/kg ($\approx$ 43,961 kJ/kg); latent heat 584 kcal/kg ($\approx$ 2,445 kJ/kg); ₹ 48,000/t.

Formula: Heat lost per kg delivered = water fraction $\times$ (GCV + latent heat); loss fraction = that $\div$ GCV; value = loss fraction $\times$ annual cost.

Substitution: $0.03 \times (10,500 + 584) = 332.5$ kcal/kg; $332.5/10,500 = 3.17\%$; $0.0317 \times 3,000 \times 48,000$.

Result: **Heat lost $\approx$ ₹ 45.6 lakh per year**: the plant pays for water that brings no heat and then spends fuel to evaporate it.

Why not the others: (c) ₹ 43.2 lakh counts only the 3% dilution and forgets the latent heat. (b) ₹ 30.4 lakh charges only the 2% above the specification limit. (a) ₹ 28.8 lakh makes both errors.

The guidebook adds that water causes flame spluttering, possible flame-out and lower flame temperature.

Ref: BEE Guidebook Paper 2, Ch. 1 (Properties of liquid fuels: water content; GCV–NCV relation).

Chapter 1: Fuels and Combustion | Heat penalty of free water in furnace oil

2. A small coal-fired boiler relies on natural draft from a 45 m chimney. Ambient air is at 35 °C; flue gas enters the chimney at 260 °C and leaves at 180 °C. Taking densities at 0 °C of 1.293 kg/m³ for air and 1.30 kg/m³ for flue gas, the theoretical draft at the chimney base is about: [4P2CEM002]

a) 16.3 mm WC ($\approx$ 160 Pa)

b) 19.2 mm WC ($\approx$ 188 Pa)

c) 21.6 mm WC ($\approx$ 212 Pa)

d) 25.8 mm WC ($\approx$ 253 Pa)

Correct answer: (b) 19.2 mm WC ($\approx$ 188 Pa).

Given: $H = 45$ m; ambient 35 °C; gas 260 °C in, 180 °C out, so mean 220 °C; ρ_o air 1.293, ρ_o gas 1.30 kg/m³.

Formula: Natural draft (kg/m², numerically mm WC) = $H \times (\rho_{\text{air}} - \rho_{\text{gas}})$, with each density corrected as $\rho = \rho_o \times 273 / (273 + t)$.

Substitution: $\rho_{\text{air}} = 1.293 \times 273 / 308 = 1.146$; $\rho_{\text{gas}} = 1.30 \times 273 / 493 = 0.720$; draft = $45 \times (1.146 - 0.720) = 19.2$ kg/m².

Result: **Draft $\approx$ 19.2 mm WC ($\approx$ 188 Pa)**. The guidebook explains natural draft as the weight difference between the hot gas column and an equal column of outside air, controlled only by dampers.

Why not the others: (d) 25.8 mm leaves outside air at its 0 °C density, ignoring the 35 °C ambient. (a) 16.3 mm uses only the 180 °C exit temperature for the whole column. (c) 21.6 mm uses only the 260 °C inlet temperature.

Ref: BEE Guidebook Paper 2, Ch. 1 (Draft system: natural draft).

Chapter 1: Fuels and Combustion | Natural draft available from a boiler chimney

3. A boiler burner on furnace oil shows long, smoky flames and carbon at the tips after a new operator reduced the air around the burner head. Which description of oil burner operation in the guidebook explains what the burner needs? [4P2CEM003]

a) Primary air atomises the oil; surrounding secondary air completes combustion

b) Secondary air atomises the oil; primary air only cools the burner tip

c) Atomisation is done by preheating alone, so burner air affects only draft

d) Finer droplets reduce surface area, so coarse spray burns more completely

Correct answer: (a) Primary air atomises the oil; surrounding secondary air completes combustion.

The guidebook explains that the primary function of a burner is to atomise fuel into millions of small droplets, increasing the surface area so that the fuel comes into intimate contact with oxygen. The finer the droplets, the more readily they meet oxygen and burn. Normally atomisation is carried out by primary air, at the centre of the burner head, and completion of combustion is ensured by the surrounding secondary air. Burner parts create high turbulence to mix air and fuel; if turbulence is insufficient, combustion is incomplete and CO appears at the stack.

Why not the others: (b) reverses the roles of primary and secondary air. (c) preheating sets viscosity for atomisation, but the burner air still atomises the oil and completes combustion. (d) finer droplets increase surface area; coarse spray gives carbon deposits and smoke.

Ref: BEE Guidebook Paper 2, Ch. 1 (Combustion of oil: oil firing burners).

Chapter 1: Fuels and Combustion | Atomisation and the roles of primary and secondary air

4. A new furnace oil handling system is being specified for a forging unit, from the tanker decanting point to the burners. Which strainer practice follows the guidebook? [4P2CEM004]

a) Coarse 10-mesh at tank entry, finer duplex strainers downstream

b) One fine strainer at tank entry; none needed downstream

c) Coarse strainers only at burners, as fine mesh chokes

d) Single fine strainers throughout, cleaned during weekly shutdowns

Correct answer: (a) Coarse 10-mesh at tank entry, finer duplex strainers downstream.

The guidebook explains that furnace oil arrives with dust, water and other contaminants, and that rags, cotton waste, loose nuts, bolts or screws can enter the system and damage the pump. A coarse strainer of 10 mesh (not more than 3

holes per linear inch) is therefore placed on the entry pipe to the storage tank. Progressively finer strainers are provided at various points in the supply system to remove finer dirt, sludge and free carbon. These filters should be in duplicate, so that one can be cleaned while oil flows through the other.

Why not the others: (b) a fine strainer at the decanting point chokes quickly with heavy, cold oil and still leaves later contamination unfiltered. (c) by the time oil reaches the burner, the pump and preheater are already exposed. (d) single strainers force a supply interruption every time they are cleaned.

Ref: BEE Guidebook Paper 2, Ch. 1 (Storage of fuel oil: removal of contaminants; Table 1.3).

Chapter 1: Fuels and Combustion | Strainer arrangement in a fuel oil system

5. In a proximate test on an Indian coal, a 1.000 g sample dried at 108 °C weighs 0.920 g. A fresh 1.000 g sample heated in a covered crucible at 900 °C weighs 0.610 g, and after the lid is removed and the carbon burnt off, 0.380 g of residue remains. The volatile matter (as-received basis) is about: [4P2CEM005]

a) 23%

b) 31%

c) 33.7%

d) 39%

Correct answer: (b) 31%.

Given: moisture loss 0.080 g; loss in covered crucible at 900 °C = 1.000 – 0.610 = 0.390 g; residue (ash) 0.380 g.

Formula: VM = (loss at 900 °C – moisture) × 100; ash = residue × 100; fixed carbon = 100 – M – VM – ash.

Substitution: moisture = 8%; VM = (0.390 – 0.080) × 100 = 31%; ash = 38%; fixed carbon = 100 – 8 – 31 – 38 = 23%.

Result: **Volatile matter ≈ 31%** on the as-received basis.

Why not the others: (d) 39% forgets that the loss at 900 °C includes moisture, as the guidebook notes. (c) 33.7% converts to a dry basis though the question asks for as-received. (a) 23% is the fixed carbon, obtained when the burnt-off carbon is mistaken for volatiles.

High volatile matter means easy ignition and more secondary air over the grate.

Ref: BEE Guidebook Paper 2, Ch. 1 (Properties of coal: measurement of moisture, volatile matter, carbon and ash).

Chapter 1: Fuels and Combustion | Volatile matter from a laboratory proximate test

6. A stoker-fired boiler burning high-ash Indian coal shows clinker on the grate. Which statement on clinker formation is WRONG? [4P2CEM006]

a) Clinker sticks more to cold, smooth surfaces than hot ones

b) Silica, CaO and MgO in ash lower its fusion temperature

c) Indian coals can show ash fusion near 1,100 °C

d) Once formed, clinker tends to keep on growing

Correct answer: (a) Clinker sticks more to cold, smooth surfaces than hot ones.

The question asks for the wrong statement. The guidebook states the opposite: clinker sticks to a hot surface rather than a cold one, and to a rough surface rather than a smooth one. That is why clinker builds up on overheated, rough refractory and grate bars.

The other statements are correct. Clinker is a hard, slag-like mass formed when ash softens because of its low fusion temperature. Silica, calcium oxide and magnesium oxide in the ash lower the fusion temperature, and Indian coals can have ash fusion temperatures as low as about 1,100 °C. Once a clinker forms it tends to grow, blocking air passages and raising unburnt losses.

Why not the others: (b), (c) and (d) are guidebook facts, so they are not the answer. Low-temperature combustion systems such as FBC (750–950 °C) avoid clinker altogether.

Ref: BEE Guidebook Paper 2, Ch. 1 (Combustion of coal: clinker formation).

Chapter 1: Fuels and Combustion | Clinker formation in coal firing

7. A ceramic tile plant is choosing between two natural gas burner types. Which description matches the guidebook?

[4P2CEM007]

- a) Low-pressure burners need gas at over 20 psi
- b) High-pressure mixers need about 40% excess air
- c) Low-pressure burners premix gas inside the fan
- d) High-pressure mixers entrain air through a venturi**

Correct answer: (d) High-pressure mixers entrain air through a venturi.

In the guidebook's high-pressure gas mixer, gas flows through a small nozzle into a venturi tube; the high-velocity jet draws in air through large openings and delivers a correctly proportioned mixture to the burner tip. A revolving shutter sets the air opening and can be locked in position.

Low-pressure burners use gas at less than 0.15 kg/cm^2 ($\approx 0.147 \text{ bar}$) (about 2 psi). They are usually multi-jet types, with small gas jets discharging around circular air openings in a heat-resisting block, and the draft may be natural, induced or forced. Excess air levels for natural gas burners are of the order of 5%.

Why not the others: (a) 20 psi is ten times the guidebook's low-pressure limit of about 2 psi. (b) 40% excess air would waste heat; gas mixes so well that about 5% suffices. (c) low-pressure burners mix gas and air at the burner block, not inside a fan.

Ref: BEE Guidebook Paper 2, Ch. 1 (Combustion of gas: low- and high-pressure gas burners).

Chapter 1: Fuels and Combustion | Low-pressure and high-pressure gas burners

8. A boiler burning 40 t/day of coal (GCV 4,000 kcal/kg ($\approx 16,747 \text{ kJ/kg}$), boiler efficiency 78%) is to switch to rice husk (GCV 3,100 kcal/kg ($\approx 12,979 \text{ kJ/kg}$), efficiency 72% on husk) for the same steam output. Bulk densities are 750 kg/m^3 for coal and 110 kg/m^3 for husk. The covered storage volume needed for 15 days of husk is about: [4P2CEM008]

- a) $5,450 \text{ m}^3$
- b) $6,500 \text{ m}^3$
- c) $7,040 \text{ m}^3$
- d) $7,620 \text{ m}^3$**

Correct answer: (d) $7,620 \text{ m}^3$.

Given: coal 40 t/day; GCV 4,000 and 3,100 kcal/kg ($\approx 12,979 \text{ kJ/kg}$); η 78% and 72%; bulk density 110 kg/m^3 for husk; 15 days.

Formula: Husk = coal $\times$ (GCV coal $\times \eta$ coal)/(GCV husk $\times \eta$ husk); volume = husk mass $\times$ days/bulk density.

Substitution: husk = $40 \times (4,000 \times 0.78)/(3,100 \times 0.72) = 55.9 \text{ t/day}$; volume = $55.9 \times 15/0.110 = 7,625 \text{ m}^3$.

Result: **Storage $\approx 7,620 \text{ m}^3$** , about 9.5 times the coal yard volume of 800 m^3 . The guidebook notes that the low bulk density of biomass raises transport and storage costs.

Why not the others: (c) $7,040 \text{ m}^3$ matches heat on GCV alone and ignores the lower efficiency on husk. (b) $6,500 \text{ m}^3$ inverts the efficiency ratio. (a) $5,450 \text{ m}^3$ scales the coal volume by bulk density only, as if a tonne of husk equalled a tonne of coal.

Ref: BEE Guidebook Paper 2, Ch. 1 (Properties of agro residues).

Chapter 1: Fuels and Combustion | Storage volume when switching from coal to rice husk

9. A 6 TPH wood-chip grate boiler shows CO and smoke whenever the under-grate air is increased to raise output.

Based on the guidebook's description of biomass combustion stages, the most appropriate correction is: [4P2CEM009]

- a) Raise under-grate air further, as char gives about 70% of heat
- b) Cut all air, as wet biomass needs less oxygen to burn fully
- c) Add secondary air above the bed, as volatiles give about 70% of heat**
- d) Raise bed depth, as moisture drying gives about 70% of heat

Correct answer: (c) Add secondary air above the bed, as volatiles give about 70% of heat.

The guidebook describes biomass combustion in stages. The particle first loses its moisture up to about 100°C , using heat released by other particles. As it heats further, volatile gases (hydrocarbons, CO, CH_4 and others) are released, and these

gases contribute about 70% of the heating value of biomass. Finally the char oxidises and ash remains. In fixed-bed grate systems, primary air passes through the bed for drying, gasification and char combustion, while the combustible gases are burned in a separate zone using secondary air.

Pushing more under-grate air only drives off more volatiles, which then leave unburnt as CO and smoke unless enough well-mixed secondary air is supplied above the bed.

Why not the others: (a) wrongly credits the char with most of the heat. (b) less air worsens incomplete combustion. (d) drying absorbs heat; it releases none.

Ref: BEE Guidebook Paper 2, Ch. 1 (Combustion of biomass).

Chapter 1: Fuels and Combustion | Combustion stages of biomass on a grate

10. After a two-week repair outage, a shift engineer wants to bring a 10 TPH oil-fired boiler from cold to pressure within an hour to meet a production deadline. Which action matches the guidebook's cold start-up procedure?

[4P2CEM010]

- a) Fill to full level and fire at maximum to save time
- b) Close all vents at light-off so that pressure builds faster
- c) Skip the purge, as the furnace was cleared before the repair work
- d) Pre-purge the furnace and keep vents open until about 1 bar**

Correct answer: (d) Pre-purge the furnace and keep vents open until about 1 bar.

The guidebook says starting up a boiler should not be speeded up and normally takes about four hours. The furnace must be pre-purged for a specified time to clear flammable gases from the gas side and avoid an explosion at light-off. The boiler is filled to slightly below the normal level, treatment chemicals may then be added, and the vents are kept open until a heavy steam jet flows out, at about 1 bar. Firing on a cold boiler must not be rushed, so that quick, uneven temperature rises do not overstrain the boiler material.

Why not the others: (a) the boiler is filled to slightly below normal level, and firing at maximum from cold overstresses the metal. (b) closing vents traps air in the steam space. (c) pre-purging is required at every start, whatever was done before.

Ref: BEE Guidebook Paper 2, Ch. 2 (Improving boiler availability: cold start-up and shutdown procedures).

Chapter 2: Boilers | Cold start-up of a boiler

11. An energy auditor sketches a boiler house following the guidebook's typical boiler system schematic. Which statement about the system agrees with the guidebook? [4P2CEM011]

- a) Feed water is returned condensate plus treated make-up; large boilers add air preheaters**
- b) Feed water is make-up water only, since returned condensate carries oil and dirt
- c) The fuel system covers condensate return, while the steam system covers burners
- d) Economisers suit only small boilers; large boilers recover heat by blowdown alone

Correct answer: (a) Feed water is returned condensate plus treated make-up; large boilers add air preheaters.

The guidebook describes the boiler system as comprising the feed water system, the steam system and the fuel system. The feed water system supplies and regulates water to meet steam demand; the steam system collects, distributes and controls the steam; and the fuel system includes the equipment that supplies fuel. Feed water has two sources: condensate returned from the processes and make-up water, which is treated raw water from outside the boiler room. In high-capacity boilers, an air preheater is installed in addition to the economiser for higher efficiency. The schematic shows an economiser, continuous blowdown heat recovery, high- and low-pressure steam use through a PRV, and a condensate return pump.

Why not the others: (b) returned condensate is a main feed source. (c) swaps the scope of the fuel and steam systems. (d) large boilers use both economisers and air preheaters.

Ref: BEE Guidebook Paper 2, Ch. 2 (Boiler systems; Figure 2.1).

Chapter 2: Boilers | Feed water sources and heat recovery points in a boiler system

12. A 65 kg/cm² ($\approx$ 63.7 bar) boiler needs make-up water almost free of dissolved salts and silica. Which description of the demineralisation plant agrees with the guidebook? [4P2CEM012]

a) Cation resin, degasser for carbonic acid, then anion resin

b) Sodium base-exchange softener followed by a degassing tower

c) Anion resin first, then cation resin regenerated with common salt

d) Cation and anion resins both regenerated with sodium chloride

Correct answer: (a) Cation resin, degasser for carbonic acid, then anion resin.

The guidebook defines demineralisation as the complete removal of all salts, as distinct from softening, which removes only hardness. Water first passes a cation resin that exchanges cations for hydrogen ions, producing hydrochloric, sulphuric and carbonic acids. Carbonic acid is removed in a degassing tower where air is blown through the acidic water. The water then passes an anion resin, which exchanges the anions of the mineral acids and forms water. The cation resin is regenerated with mineral acid and the anion resin with caustic soda; complete removal of silica depends on the correct choice of anion resin. This is why large power boilers use demineralised make-up.

Why not the others: (b) a base-exchange softener swaps calcium and magnesium for sodium and does not reduce TDS. (c) reverses the resin sequence and uses the softener regenerant. (d) salt regenerates only a base-exchange softener.

Ref: BEE Guidebook Paper 2, Ch. 2 (Boiler water treatment: external water treatment, demineralisation).

Chapter 2: Boilers | Demineralisation of boiler feed water

13. A plant drawing bore-well water with suspended matter, colour, dissolved iron and free CO₂ is commissioning a softener. What does the guidebook advise before the ion exchange stage? [4P2CEM013]

a) Feed raw water directly, since the resin bed traps suspended solids

b) Dose sodium sulphite in the raw water tank to precipitate iron

c) Remove solids and colour; aerate and sand-filter to remove iron

d) Add caustic soda ahead of the resin to neutralise the CO₂

Correct answer: (c) Remove solids and colour; aerate and sand-filter to remove iron.

The guidebook states that before any external treatment such as ion exchange, demineralisation or reverse osmosis is used, suspended solids and colour must be removed from raw water, because they foul the resins in the later stages. Pre-treatment methods include simple sedimentation in settling tanks, or clarifiers with coagulants and flocculants. For bore-well water, pressure sand filters with spray aeration are used to remove carbon dioxide and iron.

Fouled resin loses exchange capacity, so hardness slips through, scale forms and blowdown rises.

Why not the others: (a) the resin bed is not a filter; solids blind it and shorten its life. (b) sodium sulphite is an oxygen scavenger used for chemical de-aeration of feed water, not an iron remover. (d) caustic soda regenerates anion resins in demineralisation and is not a pre-treatment step.

Ref: BEE Guidebook Paper 2, Ch. 2 (Boiler water treatment: external water treatment and pre-treatment).

Chapter 2: Boilers | Pre-treatment of raw water before ion exchange

14. A coal-fired thermic fluid heater supplies fluid at 290 °C to laminate presses, and its flue gas leaves at 340 °C. Which statement on how it works and where it loses heat is consistent with the guidebook? [4P2CEM014]

a) ID fan runs continuously; shell loss is the largest loss

b) Fluid returns 10–20 °C cooler; flue loss is the major loss

c) Fluid must be pressurised to 85 bar to reach 290 °C safely

d) Flue gas leaves cooler than the fluid, so recovery is not possible

Correct answer: (b) Fluid returns 10–20 °C cooler; flue loss is the major loss.

The guidebook explains that the hot thermic fluid is circulated to process equipment and returns 10 to 20 °C cooler to be heated again. The heater works between two temperature limits: at the upper limit the burner switches off or goes to low fire, and in solid-fuel systems the ID fan switches off; at the lower limit they come on again. Because the heater operates at

250–300 °C, the exhaust gas leaves hotter than the fluid, so flue gas loss is the major component of fuel losses and offers scope for heat recovery where there is a use.

Why not the others: (a) the ID fan cycles with the temperature limits, and shell loss is minor next to the flue loss. (c) 85 bar is what steam would need for 300 °C; thermic fluid reaches it at atmospheric pressure. (d) the exhaust is necessarily hotter than the fluid.

Ref: BEE Guidebook Paper 2, Ch. 2 (Thermic fluid heaters).

Chapter 2: Boilers / Control and flue loss of a thermic fluid heater

15. Under the Indian Boiler Regulations definitions reproduced in the guidebook, which of these steam lines is a "steam pipe"? [4P2CEM015]

- a) 150 mm ID line carrying steam at 3 kg/cm²(g) ($\approx$ 2.94 bar(g))
- b) 200 mm ID line carrying steam at 0.8 kg/cm²(g) ($\approx$ 0.785 bar(g))
- c) 250 mm ID line carrying steam at 3.4 kg/cm²(g) ($\approx$ 3.33 bar(g))
- d) 300 mm ID line carrying steam at 2 kg/cm²(g) ($\approx$ 1.96 bar(g))**

Correct answer: (d) 300 mm ID line carrying steam at 2 kg/cm²(g) ($\approx$ 1.96 bar(g)).

The guidebook defines a steam pipe as any pipe through which steam passes if (i) the steam pressure exceeds 3.5 kg/cm² ($\approx$ 3.43 bar) above atmospheric pressure, or (ii) the pipe exceeds 254 mm internal diameter and the steam pressure exceeds 1 kg/cm² ($\approx$ 0.981 bar) above atmospheric, including connected fittings.

A 300 mm line at 2 kg/cm²(g) ($\approx$ 1.96 bar(g)) meets condition (ii): its bore is above 254 mm and its pressure above 1 kg/cm²(g) ($\approx$ 0.981 bar(g)).

Why not the others: (a) 150 mm at 3 kg/cm²(g) ($\approx$ 2.94 bar(g)) fails both tests: pressure is below 3.5 and bore below 254 mm. (b) 200 mm at 0.8 kg/cm²(g) ($\approx$ 0.785 bar(g)) is below both limits. (c) 250 mm at 3.4 kg/cm²(g) ($\approx$ 3.33 bar(g)) narrowly misses both: 250 mm is under 254 mm and 3.4 is under 3.5 kg/cm² ($\approx$ 3.43 bar).

Ref: BEE Guidebook Paper 2, Ch. 2 (Indian Boiler Regulation definitions).

Chapter 2: Boilers / IBR definition of a steam pipe

16. A 12 t/h boiler has no deaerator; its feed tank water at 85 °C still holds 1.2 ppm dissolved oxygen. The chemist doses commercial sodium sulphite of 95% purity (Na₂SO₃ = 126, O₂ = 32) to scavenge it, ignoring residual excess. The daily consumption of commercial sulphite is about: [4P2CEM016]

- a) 1.43 kg/day
- b) 2.59 kg/day
- c) 2.72 kg/day
- d) 2.86 kg/day**

Correct answer: (d) 2.86 kg/day.

Given: feed 12 t/h $\times$ 24 h = 288 t/day; O₂ 1.2 ppm (g/t); purity 95%; reaction $2\text{Na}_2\text{SO}_3 + \text{O}_2 \rightarrow 2\text{Na}_2\text{SO}_4$.

Formula: Sulphite = O₂ $\times$ (2 $\times$ 126/32) $\times$ feed $\div$ purity.

Substitution: $2 \times 126/32 = 7.875$ g per g O₂; pure sulphite = $1.2 \times 7.875 \times 288 = 2,722$ g/day; commercial = $2,722/0.95 = 2,865$ g/day.

Result: **About 2.86 kg/day**. The sulphate formed adds $1.2 \times 284/32 \approx 10.7$ ppm of TDS, which the guidebook says raises blowdown; hydrazine, forming nitrogen and water, is preferred in high-pressure boilers.

Why not the others: (a) 1.43 kg/day takes one mole of sulphite per mole of O₂, missing the 2:1 ratio. (c) 2.72 kg/day ignores the 95% purity. (b) 2.59 kg/day multiplies by the purity instead of dividing.

Ref: BEE Guidebook Paper 2, Ch. 2 (Boiler water treatment: chemical de-aeration).

Chapter 2: Boilers / Sodium sulphite dosing for residual oxygen in feed water

17. A process boiler will be shut down for annual inspection next week. Which water-side practice before shutdown is in line with the guidebook? [4P2CEM017]

a) **Raise blowdown 50% three to five days ahead, with more chemicals**

b) Stop all blowdown a week ahead to save heat and treated water

c) Use a few long bottom blows of several minutes each per shift

d) Lower alkalinity to near zero to avoid foaming before draining

Correct answer: (a) Raise blowdown 50% three to five days ahead, with more chemicals.

The guidebook explains that during normal operation, dissolved and suspended material is kept in suspension by water circulation and treatment chemicals. When a boiler is shut down or drained, this sludge can settle and bake on tube surfaces, sometimes needing mechanical (turbining) or chemical cleaning. Its typical procedure: three to five days before a scheduled shutdown, increase blowdown by 50%; if possible raise alkalinity to at least 500 ppm without foaming or carryover; raise scale inhibitor and oxygen scavenger feed to keep normal residuals; and raise sludge conditioner by 50–100%. In the last 24 hours, reduce continuous blowdown and increase manual blowdown.

Why not the others: (b) stopping blowdown lets sludge build up just before draining. (c) the guidebook prefers frequent short bottom blows, holding each valve open about 5–10 seconds every one to two hours. (d) alkalinity should be raised, not lowered.

Ref: BEE Guidebook Paper 2, Ch. 2 (Boiler shutdown procedures).

Chapter 2: Boilers | Boiler water practice before a planned shutdown

18. A temperature-controlled air heater battery runs at only 1.5 bar(g) in its steam space at low load. Its trap discharges into a riser that lifts condensate 7 m to an overhead return main held at 0.4 bar(g). Using the guidebook conversion for lift, the differential pressure available across the trap is about: [4P2CEM018]

a) **0.4 bar**

b) 0.7 bar

c) 0.8 bar

d) 1.1 bar

Correct answer: (a) 0.4 bar.

Given: upstream 1.5 bar(g); return main 0.4 bar(g); lift 7 m; 1 m lift $\approx$ 0.1 bar back pressure.

Formula: Back pressure = return line pressure + lift $\times$ 0.1 bar/m; differential = upstream – back pressure.

Substitution: back pressure = $0.4 + 7 \times 0.1 = 1.1$ bar; differential = $1.5 - 1.1$.

Result: **Only $\approx$ 0.4 bar is left to push condensate through the trap**, so it must be sized on this differential, or a pump-trap used.

Why not the others: (d) 1.1 bar ignores the static lift and subtracts only the main pressure. (c) 0.8 bar subtracts the lift but forgets the 0.4 bar already in the return main. (b) 0.7 bar is the lift head alone, mistaken for the differential.

The guidebook adds that the riser should enter the top of the return main and that a check valve should follow any trap lifting condensate.

Ref: BEE Guidebook Paper 2, Ch. 3 (Installation of steam traps: lifting the condensate).

Chapter 3: Steam System | Back pressure from lifting condensate after a trap

19. A 150 mm steam main has 24 flanges left uninsulated for ease of maintenance. Bare pipe of this size loses 1,250 kcal/h ($\approx$ 1.45 kW) per metre. The boiler (efficiency 85%) fires oil of GCV 10,200 kcal/kg ($\approx$ 42,705 kJ/kg) for 8,000 h/yr. Using the guidebook equivalence for an uncovered flange, the annual oil wasted is about: [4P2CEM019]

a) 8.3 tonnes

b) 14.1 tonnes

c) **16.6 tonnes**

d) 27.7 tonnes

Correct answer: (c) 16.6 tonnes.

Given: 24 flanges; bare loss 1,250 kcal/h (≈ 1.45 kW)·m; $\eta = 0.85$; GCV = 10,200 kcal/kg ($\approx 42,705$ kJ/kg); 8,000 h/yr. The guidebook equates one uncovered flange to about 0.6 m of bare pipe.

Formula: Equivalent bare length = flanges $\times$ 0.6; oil = loss $\times$ hours/($\eta \times$ GCV).

Substitution: $24 \times 0.6 = 14.4$ m; loss = $14.4 \times 1,250 = 18,000$ kcal/h; annual = $18,000 \times 8,000 = 14,400,000$ kcal; oil = $14,400,000 / (0.85 \times 10,200) = 16,609$ kg.

Result: **Oil wasted ≈ 16.6 t/yr**, so removable flange covers usually pay back quickly.

Why not the others: (d) 27.7 t takes 1 m of pipe per flange. (b) 14.1 t ignores boiler efficiency, although every kcal lost must be generated at 85%. (a) 8.3 t takes 0.3 m per flange, half the guidebook figure.

Ref: BEE Guidebook Paper 2, Ch. 3 (Steam distribution: insulation of flanges).

Chapter 3: Steam System | Heat loss from uncovered flanges

20. To cut costs, a contractor connects the condensate outlets of four steam-heated drying cans, each with a different load, to one common trap. What does the guidebook say about this? [4P2CEM020]

- a) Works if the common trap is sized for total load
- b) Works if each unit has a sight glass upstream
- c) Preferred, since one trap has fewer leakage points than four

d) Rarely works: heavily loaded units waterlog at their lower pressure

Correct answer: (d) Rarely works: heavily loaded units waterlog at their lower pressure.

The guidebook describes connecting several units to one common trap as group trapping and states that it is rarely successful, because it normally causes waterlogging and loss of output. The steam consumption of the units is never the same at any moment, so the pressures in their steam spaces differ. A heavily loaded unit condenses more steam and has a lower pressure at its drain outlet, so its condensate cannot reach the common trap against the higher-pressure condensate from lightly loaded units. The only satisfactory arrangement is individual trapping, with a trap for each unit.

Why not the others: (a) a larger common trap does not remove the pressure imbalance between steam spaces. (b) a sight glass only shows whether a trap is passing; it does not correct the imbalance. (c) fewer traps do not compensate for waterlogged, under-performing units.

Ref: BEE Guidebook Paper 2, Ch. 3 (Installation of steam traps: group trapping vs. individual trapping).

Chapter 3: Steam System | Group trapping versus individual trapping

21. Condensate at about 98 °C from a remote receiver keeps cavitating its centrifugal return pump. Which remedy is NOT among those suggested in the guidebook? [4P2CEM021]

- a) Raise the receiver or lower the pump for static head
- b) Enlarge suction piping to cut friction loss
- c) Reduce the suction pipe size to raise velocity**
- d) Use a steam-powered pressure pump instead

Correct answer: (c) Reduce the suction pipe size to raise velocity.

Hot condensate near 100 °C is close to boiling, so a centrifugal pump cavitates when the NPSH available is below the NPSH required. The guidebook gives two routes. First, increase NPSH available by raising the pressure difference between receiver and condensate, increasing static head on the suction side by lifting the receiver or lowering the pump, and increasing suction pipe dimensions to minimise friction loss. Second, use a pressure-powered (steam-driven) pump, which pushes condensate with steam pressure and cannot cavitate.

Reducing the suction pipe size increases friction loss and lowers NPSH available, making cavitation worse, so it is NOT a remedy.

Why not the others: (a) adds static head. (b) reduces suction losses. (d) is the guidebook's alternative pump type.

Returning hot condensate saves fuel, water and treatment chemicals, so pumping problems should be solved rather than dumping condensate.

Ref: BEE Guidebook Paper 2, Ch. 3 (Condensate recovery: condensate pumping).

Chapter 3: Steam System | Condensate pumping and cavitation

22. A steam survey in an old textile mill finds that 300 m of its 2,400 m insulated steam network feeds machines that were removed years ago. These lines lose 120 kcal/h (≈ 0.140 kW) per metre. The coal-fired boiler (efficiency 82%, coal GCV 4,000 kcal/kg ($\approx 16,747$ kJ/kg) at ₹ 7,000 per tonne) runs 8,000 h/yr. The annual saving from cutting out these lines is about: [4P2CEM022]

- a) ₹ 4.13 lakh
- b) ₹ 5.04 lakh
- c) ₹ 6.15 lakh**
- d) ₹ 7.38 lakh

Correct answer: (c) ₹ 6.15 lakh.

Given: redundant length 300 m; loss 120 kcal/h (≈ 0.140 kW)·m; boiler η 82%; coal GCV 4,000 kcal/kg ($\approx 16,747$ kJ/kg); ₹ 7,000/t; 8,000 h/yr.

Formula: Heat saved = length $\times$ loss $\times$ hours; coal = heat/($\eta \times$ GCV); saving = coal $\times$ price.

Substitution: $300 \times 120 = 36,000$ kcal/h; $36,000 \times 8,000 = 28,80,00,000$ kcal/yr; coal = $28,80,00,000 / (0.82 \times 4,000) = 87,805$ kg; $87.8 \text{ t} \times ₹ 7,000$.

Result: **Saving $\approx$ ₹ 6.15 lakh per year**, plus avoided trap losses and maintenance on dead legs.

Why not the others: (b) ₹ 5.04 lakh ignores boiler efficiency. (d) ₹ 7.38 lakh applies the guidebook's 15% upper bound to the whole network instead of the 300 m actually found. (a) ₹ 4.13 lakh multiplies by boiler efficiency instead of dividing.

The guidebook notes that redundant pipelines can be up to 10–15% of total length and must be eliminated, since they lose heat all year while serving nothing.

Ref: BEE Guidebook Paper 2, Ch. 3 (Energy saving opportunities: pipe redundancy).

Chapter 3: Steam System / Saving from isolating redundant steam piping

23. Steam-heated rotating drying cylinders in a paper machine heat up slowly, and the traps are found shut while the cylinders still hold condensate. The guidebook names this problem and its remedy as: [4P2CEM023]

- a) Air binding; add a thermostatic vent on the steam inlet
- b) Steam locking; use float traps with steam lock release**
- c) Water hammer; fit a liquid expansion trap at each outlet
- d) Back pressure; raise the return main above the cylinders

Correct answer: (b) Steam locking; use float traps with steam lock release.

The guidebook describes steam locking as similar to air binding, except that the trap is locked shut by steam instead of air. The typical example is a drying cylinder, where steam reaches the trap through the syphon and closes it while condensate remains in the cylinder. The recommendation is always to use a float trap fitted with a steam lock release arrangement, which bleeds the trapped steam so condensate can reach the trap.

Air binding is a different fault, in which air pumped into the trap space stops trap function and slows warm-up unless there is air venting.

Why not the others: (a) air binding involves air, and a vent at the steam inlet does not release steam trapped at the drain.

(c) a liquid expansion trap discharges cold start-up condensate from mains to waste. (d) raising the return main adds back pressure and worsens drainage.

Ref: BEE Guidebook Paper 2, Ch. 3 (Installation of steam traps: air binding and steam locking).

Chapter 3: Steam System / Steam locking in rotating drying cylinders

24. A steam main whose drain trap lifts condensate to an overhead return line suffers water hammer every morning at start-up, when main pressure is still low. Which remedy described in the guidebook addresses this? [4P2CEM024]

- a) Larger working trap so that it passes more condensate at start-up
- b) Thermodynamic trap in place of the working trap on the main
- c) Riser connected to the underside of the overhead return main
- d) Liquid expansion trap discharging cold start-up condensate to waste**

Correct answer: (d) Liquid expansion trap discharging cold start-up condensate to waste.

The guidebook explains that at start-up the steam pressure in a main is very low, so it cannot lift condensate against the back pressure of the riser and water backs up before the trap, which can cause water hammer. A liquid expansion trap fitted ahead of the working trap discharges the cold condensate formed at this time to waste. As the main warms, the condensate temperature rises and the liquid expansion trap closes; by then the steam pressure has risen enough to force hot condensate through the working trap to the return line.

Why not the others: (a) a bigger trap cannot discharge when there is no pressure difference to drive the lift. (b) a thermodynamic trap faces the same lack of differential. (c) the guidebook prefers the riser to enter the top of the return main; a bottom entry fills with condensate and increases water hammer.

Ref: BEE Guidebook Paper 2, Ch. 3 (Installation of steam traps: lifting the condensate).

Chapter 3: Steam System | Liquid expansion trap on a steam main at start-up

25. A process needs 4,500 kg/h of steam at 3 kg/cm²(g) (≈ 2.94 bar(g)), now supplied from the 10 kg/cm²(g) (≈ 9.81 bar(g)) boiler main (enthalpy 664 kcal/kg ($\approx 2,780$ kJ/kg)) through a PRV. A thermocompressor will entrain 1,500 kg/h of flash steam at 0.5 kg/cm²(g) (≈ 0.490 bar(g)) using boiler steam as motive steam, delivering the same 4,500 kg/h. With feed water at 60 °C, boiler efficiency 85% and oil GCV 10,200 kcal/kg ($\approx 42,705$ kJ/kg), the oil saved in 8,000 h/yr is about: [4P2CEM025]

a) 711 tonnes

b) 836 tonnes

c) 919 tonnes

d) 1,672 tonnes

Correct answer: (b) 836 tonnes.

Given: discharge 4,500 kg/h; suction 1,500 kg/h; motive = 4,500 – 1,500 = 3,000 kg/h; h steam 664 kcal/kg ($\approx 2,780$ kJ/kg); feed 60 kcal/kg (≈ 251 kJ/kg); η 0.85; GCV 10,200 kcal/kg ($\approx 42,705$ kJ/kg); 8,000 h.

Formula: Boiler steam saved = entrained flash steam; oil = saved steam $\times$ (h steam – h feed)/($\eta \times$ GCV) $\times$ hours.

Substitution: $1,500 \times (664 - 60) / (0.85 \times 10,200) = 104.5$ kg/h; $\times 8,000 = 8,36,000$ kg.

Result: **Oil saved ≈ 836 t/yr.** The guidebook notes that the major energy in steam is its latent heat, so recompressing flash steam with motive steam gives a large waste heat recovery.

Why not the others: (a) 711 t ignores boiler efficiency. (c) 919 t ignores the feed water enthalpy, crediting heat the boiler never supplied. (d) 1,672 t treats the 3,000 kg/h motive steam as saved, though it still comes from the boiler.

Ref: BEE Guidebook Paper 2, Ch. 3 (Thermocompressor).

Chapter 3: Steam System | Boiler steam saved by a thermocompressor on flash steam

26. A forging furnace has standing losses (walls, openings and water cooling) of 3.6 lakh kcal/h (≈ 419 kW) at operating temperature. Each batch is held 45 minutes longer than metallurgically required; there are 10 batches a day for 300 days. Only 40% of the oil's heat (GCV 10,200 kcal/kg ($\approx 42,705$ kJ/kg)) is available in the furnace after flue gas loss. The oil wasted per year is about: [4P2CEM026]

a) 79.4 tonnes

b) 132.4 tonnes

c) 198.5 tonnes

d) 264.7 tonnes

Correct answer: (c) 198.5 tonnes.

Given: standing loss 3,60,000 kcal/h (≈ 419 kW); extra time 0.75 h per batch; 3,000 batches/yr; available heat 40%; GCV 10,200 kcal/kg ($\approx 42,705$ kJ/kg).

Formula: Extra heat = loss rate $\times$ extra hours; oil = extra heat/(available heat fraction $\times$ GCV).

Substitution: extra hours = $0.75 \times 3,000 = 2,250$ h; heat = $3,60,000 \times 2,250 = 81,00,00,000$ kcal; oil = $81,00,00,000 / (0.40 \times 10,200) = 1,98,529$ kg.

Result: **Oil wasted ≈ 198.5 t/yr,** plus extra scale on the forgings.

Why not the others: (a) 79.4 t divides by full GCV, forgetting that 60% of every kilogram's heat leaves with the flue gas. (d) 264.7 t takes one hour per batch. (b) 132.4 t divides by 60%, mistaking the flue loss for the available heat. The guidebook stresses that stock should stay only for the minimum time needed, as loss per unit time rises with temperature.

Ref: BEE Guidebook Paper 2, Ch. 4 (Furnace energy conservation: optimum residence time).

Chapter 4: Furnaces | Fuel wasted by excess soaking time

27. After commissioning O₂ trim on both units, a plant head asks why the forge reheating furnace is still near 25% efficient while the boiler beside it reaches 82%. Which explanation reflects the guidebook's fundamental reason?

[4P2CEM027]

- a) Furnace oil burns less completely at furnace flame temperatures
- b) Flue gas cannot leave cooler than the hot charge it heats**
- c) Refractory walls absorb more heat than water-cooled boiler tubes
- d) Furnaces must run far higher excess air to protect the stock

Correct answer: (b) Flue gas cannot leave cooler than the hot charge it heats.

The guidebook explains that one reason for the difference in thermal efficiency between boiler furnaces and industrial furnaces lies in the final temperature of the material being heated. Gases can give up heat to the charge only as long as they are hotter than the charge, so the flue gases must leave an industrial furnace at a very high temperature, except for a short time after a cold start. A boiler heats water at 150–250 °C and can cool its gas to near 200 °C, while a forge furnace heating steel to 1,200 °C discharges gas well above 1,000 °C.

Hence waste heat recovery is the main route to higher efficiency.

Why not the others: (a) oil combustion is complete at furnace temperatures with correct air. (c) wall losses are real but secondary to stack loss. (d) high excess air is a fault to correct, not a requirement.

Ref: BEE Guidebook Paper 2, Ch. 4 (Performance evaluation: reasons for low furnace efficiency).

Chapter 4: Furnaces | Why furnace efficiency stays below boiler efficiency

28. A foundry cupola is to melt 24 t of pig iron and foundry returns in a shift. Using the guidebook's most common iron-to-coke ratio and its rule for limestone flux, the coke and limestone to be charged are about: [4P2CEM028]

- a) 3.0 t coke and 4.8 t limestone
- b) 2.7 t coke and 0.53 t limestone
- c) 3.0 t coke and 0.6 t limestone**
- d) 3.0 t coke and 0.38 t limestone

Correct answer: (c) 3.0 t coke and 0.6 t limestone.

Given: metal charge = 24 t; iron-to-coke ratio 8 : 1; flux $\approx$ one-fifth of the coke weight.

Formula: Coke = metal/8; limestone = coke/5.

Substitution: coke = 24/8 = 3.0 t; limestone = 3.0/5 = 0.6 t.

Result: $\approx$ **3.0 t coke and 0.6 t limestone per shift**, charged in alternate layers of coke, flux and metal.

Why not the others: (a) 4.8 t takes one-fifth of the metal, not of the coke. (b) 2.7 t treats 8 : 1 as the iron share of iron plus coke (24 $\times$ 1/9). (d) 0.38 t applies the 8 : 1 ratio again to the flux.

The flux melts and reacts with impurities to form slag, which floats on the molten metal and protects it from oxidation. The cupola works on the counter-current principle: rising gases preheat the descending charge.

Ref: BEE Guidebook Paper 2, Ch. 4 (Types of furnaces: cupola furnace).

Chapter 4: Furnaces | Coke and flux charge of a cupola

29. A foundry's cupola exhaust leaves at about 800 °C and contains CO. The energy manager proposes a hot blast cupola. Which statement agrees with the guidebook? [4P2CEM029]

- a) Blast air can reach 400 °C; above 300 °C it raises combustion temperature**

- b) Blast air can reach only 150 °C, since exhaust CO cannot be burnt
- c) Preheating blast air slows coke combustion and lowers the melting temperature
- d) Hot blast is used only to dry the charge, not to support combustion

Correct answer: (a) Blast air can reach 400 °C; above 300 °C it raises combustion temperature.

The guidebook notes that cupola exhaust gas can be as hot as 800 °C, so blast air can be preheated to as high as 400 °C by heat exchange. Both the sensible heat and the latent (chemical) heat of the exhaust can be recycled, because the CO in the exhaust can be burnt to help preheat the blast. When blast air is preheated to 300 °C or more, its sensible heat adds to the heat input, activates the combustion of coke and raises the combustion temperature.

In practice this lowers coke per tonne of metal and gives hotter metal at the spout.

Why not the others: (b) understates the achievable preheat and wrongly rules out burning the CO. (c) reverses the effect: hot blast intensifies coke combustion. (d) the charge is already preheated by rising gases in the preheating zone; the hot blast enters through the tuyeres for combustion.

Ref: BEE Guidebook Paper 2, Ch. 4 (Types of furnaces: cupola furnace, hot blast cupola).

Chapter 4: Furnaces | Hot blast operation of a cupola

30. A foundry needs hot air for sand drying and core ovens and is buying an oil-fired hot air generator. Which description matches the guidebook? [4P2CEM030]

- a) Air is heated through metal tubes only, so combustion products never reach the air
- b) The mixing chamber is lined with firebrick and the combustion chamber with insulating brick
- c) Burner gases mix with dilution air in a venturi; firebrick chamber, insulating brick downstream**
- d) It works only on natural gas, as oil flames cannot be diluted to drying temperature

Correct answer: (c) Burner gases mix with dilution air in a venturi; firebrick chamber, insulating brick downstream.

The guidebook describes hot air generators as supplying air heated to an elevated temperature by mixing it with the products of combustion from a burner. The unit consists of an inner refractory combustion chamber, a venturi section where hot products of combustion mix with dilution air, and an outlet section. The combustion chamber is lined with firebrick, while the mixing chamber and outlet section are lined with insulation brick. Furnace oil, HSD, LDO, LPG or natural gas may be used, and applications include foundry sand drying, shell sand coating, core drying, tea and seed drying and paint drying.

Why not the others: (a) describes an indirect air heater; the guidebook unit mixes combustion products into the air. (b) reverses the linings: firebrick faces the flame, insulating brick the cooler mixed gas. (d) the guidebook lists several liquid fuels as well as gas.

Ref: BEE Guidebook Paper 2, Ch. 4 (Types of furnaces: hot air generator).

Chapter 4: Furnaces | Construction of an oil-fired hot air generator

31. An insulation contractor groups materials for a plant standard. Which grouping and property statement is consistent with the guidebook? [4P2CEM031]

- a) Organic: mineral wool, calcium silicate; EPS is inorganic
- b) Organic: EPS, PUF; calcium silicate is inorganic for 40–950 °C**
- c) Inorganic: PUF, EPS; calcium silicate is organic for 40–950 °C
- d) Inorganic: EPS only; mineral wool is organic for above 1,000 °C

Correct answer: (b) Organic: EPS, PUF; calcium silicate is inorganic for 40–950 °C.

The guidebook classifies insulation materials into organic and inorganic types. Organic insulations are based on hydrocarbon polymers that can be expanded into high-void structures; examples are thermocol (expanded polystyrene, EPS) and polyurethane foam (PUF). Inorganic insulation is based on siliceous, aluminous or calcium materials in fibrous, granular or powder form; examples are mineral wool and calcium silicate. Calcium silicate is used on process piping needing high service temperature and compressive strength, over about 40 °C to 950 °C.

Organic foams therefore suit low-temperature and cold service, while inorganic materials suit hot surfaces.

Why not the others: (a) puts mineral wool and calcium silicate in the organic group. (c) reverses the classes and calls calcium silicate organic. (d) calls mineral wool organic and assigns it a temperature range the guidebook does not give.
Ref: BEE Guidebook Paper 2, Ch. 5 (Insulation: insulation materials and their properties).

Chapter 5: Insulation and Refractories | Organic and inorganic insulation materials

32. Furnace oil (5,000 kg/h, specific heat 0.5 kcal/kg °C (≈ 2.09 kJ/kg·K)) flows from a day-tank heater to the burners through a 250 m outdoor 80 NB line that is bare. At the line temperature the bare pipe loses 180 kcal/h (≈ 0.209 kW) per metre. To have the oil at 105 °C at the burners, the oil must leave the heater at about: [4P2CEM032]

- a) 87 °C
- b) 114 °C
- c) 123 °C**
- d) 141 °C

Correct answer: (c) 123 °C.

Given: $m = 5,000$ kg/h; $C_p = 0.5$ kcal/kg °C (≈ 2.09 kJ/kg·K); $L = 250$ m; loss 180 kcal/h (≈ 0.209 kW)·m; required 105 °C at the burners.

Formula: Line loss = $L \times \text{loss per metre} = m \times C_p \times \Delta T$, so $\Delta T = L \times q / (m \times C_p)$; heater outlet = burner temperature + ΔT .

Substitution: loss = $250 \times 180 = 45,000$ kcal/h; $\Delta T = 45,000 / (5,000 \times 0.5) = 18$ °C; outlet = $105 + 18 = 123$ °C.

Result: **Heater outlet ≈ 123 °C.** Maintaining process temperature is a purpose of insulation in the guidebook; insulating the line removes most of this drop.

Why not the others: (b) 114 °C uses the specific heat of water (1.0) for oil. (a) 87 °C subtracts the drop instead of adding it. (d) 141 °C counts the loss twice, as if a return line of equal length were in series with the supply.

Ref: BEE Guidebook Paper 2, Ch. 5 (Purpose of insulation; heat loss from bare surfaces).

Chapter 5: Insulation and Refractories | Oil temperature drop along an uninsulated transfer line

33. A dairy needs insulation for (i) chilled-water lines and air-conditioning ducts, (ii) a 600 °C hot-gas duct that must support some load, and (iii) a pump house wall where noise and fire safety matter. Which choice agrees with the guidebook's material descriptions? [4P2CEM033]

- a) (i) nitrile rubber, (ii) calcium silicate, (iii) rock wool**
- b) (i) calcium silicate, (ii) glass wool, (iii) thermocol
- c) (i) rock wool, (ii) thermocol, (iii) nitrile rubber
- d) (i) glass wool, (ii) nitrile rubber, (iii) calcium silicate

Correct answer: (a) (i) nitrile rubber, (ii) calcium silicate, (iii) rock wool.

The guidebook describes expanded nitrile rubber as a flexible material forming a closed-cell integral vapour barrier, developed for condensation control on refrigeration and chilled-water lines and now used on air-conditioning ducting.

Calcium silicate is used on process piping where high service temperature and compressive strength are needed, over about 40–950 °C. Rock mineral wool gives good thermal and acoustic insulation and is fire retardant. Glass mineral wool suits –10 to 500 °C, and thermocol is mainly a cold insulation.

Why not the others: (b) glass wool is unsuited above 500 °C, and thermocol is neither fire retardant nor acoustic insulation. (c) thermocol cannot be used on a 600 °C duct. (d) nitrile rubber cannot take 600 °C, and glass wool lacks the closed-cell vapour barrier needed on chilled lines.

Ref: BEE Guidebook Paper 2, Ch. 5 (Insulation: types and application, properties of common insulating materials).

Chapter 5: Insulation and Refractories | Choosing among common insulating materials

34. A 20 TPH bubbling FBC boiler in a cotton belt fires a mix of cotton stalk, rice husk and red gram husk. Which pairing of fuel and problem matches the guidebook? [4P2CEM034]

- a) Rice husk sulphur causes cold-end corrosion of the economiser
- b) Red gram husk silica erodes superheater and economiser coils

c) Cotton stalk silica causes bed defluidisation at 600 °C

d) Cotton stalk chlorides with Na and K aggravate superheater corrosion

Correct answer: (d) Cotton stalk chlorides with Na and K aggravate superheater corrosion.

The guidebook's application considerations for biomass FBC boilers include several fuel-specific problems. Chloride content in some biomass, such as cotton stalk at 8–9%, combines with sodium and potassium in the high-temperature zone and aggravates corrosion, especially of superheater tubes. High silica, especially in rice husk, causes frequent erosion of superheater and economiser coils. Red gram husk and twigs cause cold-end corrosion of the secondary superheater and economiser tubes because of their sulphur content.

It also notes that a mix of 6–7 biomass types makes a workable air-fuel ratio hard to set, and that high moisture jams feeders and causes pressure fluctuations.

Why not the others: (a) gives rice husk the sulphur problem that belongs to red gram husk. (b) gives red gram husk the silica erosion that belongs to rice husk. (c) mislinks cotton stalk to silica, and 600 °C is below normal bed temperature.

Ref: BEE Guidebook Paper 2, Ch. 6 (Application considerations with biomass FBC boilers).

Chapter 6: FBC Boilers | Operating problems in biomass-fired FBC boilers

35. A CFBC boiler burns 12 t/h of coal with a theoretical air requirement of 5.6 kg/kg and runs at 20% excess air. Following the guidebook description of CFBC, primary fluidising air is 65% of the total air. The secondary air the SA fan must deliver is about: [4P2CEM035]

a) 23.5 t/h

b) 28.2 t/h

c) 37.0 t/h

d) 52.4 t/h

Correct answer: (b) 28.2 t/h.

Given: coal 12 t/h; theoretical air 5.6 kg/kg; excess air 20%; primary air 65% of total.

Formula: Total air = coal × theoretical air × (1 + EA); secondary air = total × (1 – PA fraction).

Substitution: total = 12 × 5.6 × 1.20 = 80.64 t/h; secondary = 80.64 × 0.35 = 28.22 t/h.

Result: **Secondary air ≈ 28.2 t/h.** The guidebook states that in CFBC the primary air (60–70% of total) fluidises the bed, the balance is admitted above it as secondary air, and FBC boilers run at only 20–25% excess air.

Why not the others: (a) 23.5 t/h takes 35% of theoretical air, leaving out the excess air. (c) 37.0 t/h subtracts 65% of theoretical air from the total, mixing two bases. (d) 52.4 t/h assigns the 65% share to secondary air.

Ref: BEE Guidebook Paper 2, Ch. 6 (Circulating fluidised bed combustion).

Chapter 6: FBC Boilers | Secondary air quantity in a CFBC boiler

36. In a bubbling fluidised bed, the mean velocity of the solids rises more slowly than the gas velocity. As per the guidebook, what is the term for this difference and what is desirable? [4P2CEM036]

a) Slip velocity; a minimum value prevents particle entrainment

b) Terminal velocity; a maximum value lowers fan power

c) Slip velocity; a maximum value aids heat transfer and contact

d) Fluidisation velocity; a zero value gives a stable bed

Correct answer: (c) Slip velocity; a maximum value aids heat transfer and contact.

The guidebook explains that the mean solids velocity increases more slowly than the gas velocity, and that the difference between the mean solid velocity and the mean gas velocity is called slip velocity. Maximum slip velocity between solids and gas is desirable for good heat transfer and intimate contact.

The bed must operate within a window: above the minimum fluidisation velocity, at which the bed first lifts and behaves like a fluid, and below the entrainment (transport) velocity, at which particles are carried out of the furnace. Coal burns rapidly in the hot sand bed at about 840–950 °C, below ash fusion temperature.

Why not the others: (a) reverses the guidebook's advice; entrainment is controlled by keeping gas velocity below the transport velocity, not by minimising slip. (b) terminal velocity describes particle carry-over, and its link to fan power is wrong. (d) zero slip means no fluidisation benefit.

Ref: BEE Guidebook Paper 2, Ch. 6 (Mechanism of fluidised bed combustion).

Chapter 6: FBC Boilers | Slip velocity and the fluidisation window

37. A back-pressure turbine takes 20 t/h of steam at 766 kcal/kg ($\approx 3,207$ kJ/kg) and exhausts to process at 3 kg/cm²(g) (≈ 2.94 bar(g)) with an actual exhaust enthalpy of 671 kcal/kg ($\approx 2,809$ kJ/kg). Process now demands 6 kg/cm²(g) (≈ 5.88 bar(g)), raising the actual exhaust enthalpy to 689 kcal/kg ($\approx 2,885$ kJ/kg) at the same flow. With combined gearbox and generator efficiency 92%, the loss of electrical output is about: [4P2CEM037]

a) 145 kW

b) 385 kW

c) 419 kW

d) 455 kW

Correct answer: (b) 385 kW.

Given: 20,000 kg/h; h_{in} 766 kcal/kg ($\approx 3,207$ kJ/kg); h_{out} 671 $\rightarrow$ 689 kcal/kg ($\approx 2,885$ kJ/kg); $\eta = 0.92$; 1 kW = 860 kcal/h.

Formula: Power = $m \times (h_{in} - h_{out}) \times \eta / 860$; loss = $m \times \Delta h_{out} \times \eta / 860$.

Substitution: before = $20,000 \times 95 \times 0.92 / 860 = 2,033$ kW; after = $20,000 \times 77 \times 0.92 / 860 = 1,647$ kW; loss = $20,000 \times 18 \times 0.92 / 860 = 385$ kW.

Result: **Output falls by ≈ 385 kW (19%)**. The guidebook notes that a back-pressure turbine's power is fixed by the process exhaust pressure, so higher process pressure costs generation.

Why not the others: (c) 419 kW omits the gearbox and generator efficiency. (d) 455 kW divides by the efficiency instead of multiplying. (a) 145 kW scales output by the pressure change over inlet pressure (3/42), which is not how enthalpy drop varies.

Ref: BEE Guidebook Paper 2, Ch. 7 (Back pressure turbine; steam turbine efficiency).

Chapter 7: Cogeneration | Power lost when a back-pressure turbine exhaust pressure is raised

38. A gas turbine cogeneration plant cannot meet a new steam demand from its unfired HRSG. Why does the guidebook regard supplementary firing as an efficient way to boost thermal output? [4P2CEM038]

a) Turbine exhaust is cool, so the duct burner adds heat at low temperature

b) Duct firing raises turbine power, which lowers the heat-to-power ratio

c) It lets the gas turbine burn cheaper residual fuels in its combustor

d) Turbine exhaust is oxygen-rich, so extra fuel burns without extra air

Correct answer: (d) Turbine exhaust is oxygen-rich, so extra fuel burns without extra air.

The guidebook explains that a gas turbine has low heat-to-power conversion efficiency but its heat is recovered at high temperature. If the heat output is less than the user requires, supplementary natural gas firing is possible by mixing additional fuel with the oxygen-rich exhaust gas, which boosts the thermal output more efficiently. Because a gas turbine runs with large excess air, its exhaust still holds ample oxygen, so the duct burner needs no fresh combustion air and adds little extra stack gas.

If more power rather than heat is needed, the guidebook instead suggests a combined cycle with a steam turbine.

Why not the others: (a) gas turbine exhaust is at about 450–550 °C, which is hot, not cool. (b) duct firing raises heat output only; turbine power is unchanged, so the heat-to-power ratio rises. (c) the burner is in the exhaust duct; the turbine combustor still needs premium, clean fuel.

Ref: BEE Guidebook Paper 2, Ch. 7 (Gas turbine cogeneration systems).

Chapter 7: Cogeneration | Supplementary firing in a gas turbine HRSG

39. A cogeneration plant burns fuel equivalent to 2.6×10^7 kcal/h (≈ 30.2 MW) while delivering 1.4×10^7 kcal/h (≈ 16.3 MW) of useful process heat and 3,800 kW of power. The alternative stand-alone boiler for the same heat would be 85% efficient. The fuel chargeable to power (heat rate) is about: [4P2CEM039]

- a) 1,930 kcal/kWh ($\approx 8,081$ kJ/kWh)
- b) 2,507 kcal/kWh ($\approx 10,496$ kJ/kWh)**
- c) 3,158 kcal/kWh ($\approx 13,222$ kJ/kWh)
- d) 6,842 kcal/kWh ($\approx 28,646$ kJ/kWh)

Correct answer: (b) 2,507 kcal/kWh ($\approx 10,496$ kJ/kWh).

Given: total fuel 2,600,000 kcal/h (≈ 30.2 MW); process heat 1,400,000 kcal/h (≈ 16.3 MW); power 3,800 kW; alternative boiler η 85%.

Formula: Fuel chargeable to power = (total fuel – process heat/ η boiler)/power.

Substitution: fuel credited to heat = $1,400,000/0.85 = 1,64,70,588$ kcal/h; fuel for power = $2,600,000 - 1,64,70,588 = 95,29,412$ kcal/h; $95,29,412/3,800$.

Result: **FCP $\approx 2,507$ kcal/kWh ($\approx 10,496$ kJ/kWh)**, far lower than the 2,500–3,000 kcal/kWh ($\approx 12,560$ kJ/kWh)-plus heat rates of stand-alone condensing plants once their losses are included.

Why not the others: (d) 6,842 kcal/kWh ($\approx 28,646$ kJ/kWh) charges all fuel to power and gives no credit for the heat. (c) 3,158 kcal/kWh ($\approx 13,222$ kJ/kWh) credits heat at 100% boiler efficiency. (a) 1,930 kcal/kWh ($\approx 8,081$ kJ/kWh) credits heat at a 75% boiler, flattering the plant.

Ref: BEE Guidebook Paper 2, Ch. 7 (Cogeneration heat rate and efficiency assessment).

Chapter 7: Cogeneration | Fuel chargeable to power in a cogeneration plant

40. A forging furnace exhausts 6,000 kg/h of flue gas at 700 °C (specific heat 0.26 kcal/kg °C (≈ 1.09 kJ/kg·K)). In a cascade recovery scheme, a recuperator first cools the gas to 400 °C to preheat combustion air, and a second-stage water heater then cools it to 170 °C, heating process water from 30 °C to 85 °C. Neglecting losses, the hot water produced is about: [4P2CEM040]

- a) 4,221 kg/h
- b) 6,524 kg/h**
- c) 8,509 kg/h
- d) 15,033 kg/h

Correct answer: (b) 6,524 kg/h.

Given: gas 6,000 kg/h, C_p 0.26 kcal/kg °C (≈ 1.09 kJ/kg·K); stage 1 700 $\rightarrow$ 400 °C; stage 2 400 $\rightarrow$ 170 °C; water 30 $\rightarrow$ 85 °C.

Formula: Stage-2 duty = $m_g \times C_p \times (400 - 170)$; water = duty $\div (1 \times (85 - 30))$.

Substitution: $6,000 \times 0.26 \times 230 = 3,58,800$ kcal/h; $3,58,800 \div 55$.

Result: **Hot water $\approx 6,524$ kg/h.** The recuperator has already taken 4,68,000 kcal/h (≈ 544 kW) for air preheat, so the cascade recovers the gas heat at two temperature levels.

Why not the others: (d) 15,033 kg/h credits the water heater with all the heat from 700 °C. (a) 4,221 kg/h divides by the 85 °C outlet temperature instead of the 55 °C rise. (c) 8,509 kg/h uses the recuperator duty instead of the water heater's.

Ref: BEE Guidebook Paper 2, Ch. 8 (Heat losses – quality: cascade waste heat recovery).

Chapter 8: Waste Heat Recovery | Cascade waste heat recovery - hot water from the low-temperature stage

41. An incinerator vendor offers a waste heat boiler for exhaust gas in the medium temperature range. Which feature or practice matches the guidebook's description? [4P2CEM041]

- a) Finned water tubes for compactness, with auxiliary burners if heat falls short**
- b) Fire tubes only, since water-tube designs cannot use waste gases
- c) Steam pressure is fixed by the feed pump, whatever the gas temperature
- d) Plain tubes are mandatory, as finned tubes cannot be used on gas side

Correct answer: (a) Finned water tubes for compactness, with auxiliary burners if heat falls short.

The guidebook describes waste heat boilers as ordinarily water-tube boilers in which hot exhaust gases from gas turbines, incinerators and similar sources pass over parallel tubes containing water; the steam is collected in a steam drum. Because the exhaust gases are usually in the medium temperature range, a more compact boiler is produced by finning the water tubes to increase the effective heat transfer area on the gas side. The pressure and rate of steam generation depend on the temperature of the waste heat. If the waste heat is insufficient for the required process steam, auxiliary burners or an after-burner in the flue are added.

Why not the others: (b) the guidebook describes them as ordinarily water-tube boilers. (c) the achievable steam pressure is limited by the waste gas temperature through saturation conditions. (d) finned tubes are exactly what the guidebook recommends for compactness.

Ref: BEE Guidebook Paper 2, Ch. 8 (Commercial waste heat recovery devices: waste heat boilers).

Chapter 8: Waste Heat Recovery | Design features of waste heat boilers

42. Before designing heat recovery from a spray dryer's exhaust, an energy manager reviews process flow sheets, layouts and piping isometrics. Which set of items does the guidebook say this review must identify? [4P2CEM042]

a) Vendor list, spare parts, painting schedule and warranty terms

b) Heat sources and uses, upset conditions, space, dew point limits

c) Only exhaust temperature, as flow and use follow automatically

d) Only the payback period, decided before any process review

Correct answer: (b) Heat sources and uses, upset conditions, space, dew point limits.

The guidebook's steps for developing a waste heat recovery system begin with understanding the process: reviewing process flow sheets, layout diagrams, piping isometrics and electrical and instrumentation cable ducting. This review identifies (a) sources and uses of waste heat, (b) upset conditions that heat recovery may cause in the plant, (c) availability of space, and (d) other constraints such as dew point occurring in equipment.

Only then is a suitable recovery system selected, followed by economic evaluation (investment, depreciation, payback, rate of return) and advice from experienced consultants and suppliers. For a spray dryer, sticky powder fouling and cooling the exhaust below its dew point are typical constraints.

Why not the others: (a) these are procurement details, not process understanding. (c) temperature alone ignores quantity, availability over time and matching with a heat sink. (d) economics comes after technical feasibility, not before the process review.

Ref: BEE Guidebook Paper 2, Ch. 8 (Development of a waste heat recovery system).

Chapter 8: Waste Heat Recovery | Understanding the process before designing heat recovery

43. A plate pasteuriser handles 10,000 litres/h of milk (density 1.03 kg/litre, specific heat 0.93 kcal/kg °C (≈ 3.89 kJ/kg·K)), heating it from 4 °C to 72 °C. Its regeneration section uses outgoing pasteurised milk to heat raw milk to 61 °C. If the replaced heat would otherwise come from steam at 3 kg/cm²(g) (latent heat 510 kcal/kg ($\approx 2,135$ kJ/kg)), total enthalpy 653 kcal/kg ($\approx 2,734$ kJ/kg)), the steam saved is about: [4P2CEM043]

a) 836 kg/h

b) 1,013 kg/h

c) 1,039 kg/h

d) 1,071 kg/h

Correct answer: (d) 1,071 kg/h.

Given: 10,000 litres/h $\times 1.03 = 10,300$ kg/h; C_p 0.93 kcal/kg °C (≈ 3.89 kJ/kg·K); regeneration 4 $\rightarrow$ 61 °C; latent heat 510 kcal/kg ($\approx 2,135$ kJ/kg).

Formula: Heat recovered = $m \times C_p \times \Delta T$; steam saved = heat/latent heat (indirect heating returns condensate).

Substitution: $10,300 \times 0.93 \times 57 = 5,46,003$ kcal/h; $5,46,003/510 = 1,071$ kg/h.

Result: **Steam saved $\approx 1,071$ kg/h**, with a regeneration efficiency of $57/68 = 84\%$. The guidebook lists the pasteurisation section of milk plants as a typical plate heat exchanger application.

Why not the others: (a) 836 kg/h divides by total enthalpy, wrong when only latent heat is given up and condensate leaves hot. (b) 1,013 kg/h uses latent heat at atmospheric pressure (539). (c) 1,039 kg/h treats litres as kilograms and drops the density.

Ref: BEE Guidebook Paper 2, Ch. 8 (Plate heat exchanger).

Chapter 8: Waste Heat Recovery | Steam saved by the regeneration section of a milk pasteuriser

44. A paint oven exhausts 12,000 kg/h of air at 160 °C, far from the fresh-air intake, so a run-around coil is proposed. The exhaust coil cools the air to 90 °C, and the glycol loop loses 5% of the recovered heat in its piping. The fresh air supply of 15,000 kg/h enters at 30 °C. Taking C_p of air as 0.24 kcal/kg °C (≈ 1.00 kJ/kg·K), the fresh air leaves its coil at about: [4P2CEM044]

a) 83.2 °C

b) 86.0 °C

c) 88.8 °C

d) 96.5 °C

Correct answer: (a) 83.2 °C.

Given: exhaust 12,000 kg/h, 160 → 90 °C; fresh air 15,000 kg/h at 30 °C; $C_p = 0.24$ kcal/kg °C (≈ 1.00 kJ/kg·K); loop loss 5%.

Formula: Recovered heat $Q = m_{\text{exhaust}} \times C_p \times \Delta T$; delivered = 0.95 Q ; fresh air outlet = 30 + delivered/($m_{\text{fresh}} \times C_p$).

Substitution: $Q = 12,000 \times 0.24 \times 70 = 2,01,600$ kcal/h; delivered = 1,91,520 kcal/h; rise = $1,91,520 / (15,000 \times 0.24) = 53.2$ °C.

Result: **Fresh air ≈ 83.2 °C.** The guidebook describes the run-around coil as two coils linked by a pumped heat transfer fluid, useful when hot and cold streams are far apart.

Why not the others: (b) 86.0 °C ignores the 5% loop loss. (c) 88.8 °C adds the loss instead of subtracting it. (d) 96.5 °C assumes equal air flows, so the fresh air rises by the same 70 °C less 5%.

Ref: BEE Guidebook Paper 2, Ch. 8 (Run around coil exchanger).

Chapter 8: Waste Heat Recovery | Fresh air temperature from a run-around coil system

45. A design engineer compares a coil-type exchanger, a shell-and-tube exchanger and a plate exchanger for a duty. Which ranking agrees with the guidebook? [4P2CEM045]

a) **Performance: plate > shell-and-tube > coil; pressure: coil > shell-and-tube > plate**

b) Performance: coil > shell-and-tube > plate; pressure: plate > shell-and-tube > coil

c) Performance: shell-and-tube > plate > coil; pressure: plate > coil > shell-and-tube

d) Performance: plate > coil > shell-and-tube; pressure: shell-and-tube > plate > coil

Correct answer: (a) Performance: plate > shell-and-tube > coil; pressure: coil > shell-and-tube > plate.

The guidebook states that the thermal performance of a shell-and-tube exchanger usually surpasses that of a coil type but is less than that of a plate type, while its pressure capability is generally higher than a plate type but lower than a coil type. Plate exchangers have corrugated plates that raise turbulence, giving high heat transfer coefficients, low pressure drop and very high effectiveness, but relatively low pressure capability. In a shell-and-tube unit the process fluid usually goes inside the tubes for ease of cleaning or to use the higher pressure capability inside the tubes.

So a high-pressure duty may rule out a plate unit even where its effectiveness is attractive.

Why not the others: (b) reverses both rankings. (c) places plate units highest in pressure, the opposite of the guidebook.

(d) puts coils above shell-and-tube in performance and plates above coils in pressure capability.

Ref: BEE Guidebook Paper 2, Ch. 9 (Heat exchanger types by construction).

Chapter 9: Heat Exchangers | Thermal performance and pressure capability by construction

46. In a refinery crude distillation tower, live steam is injected at the bottom of the tower in addition to the furnace heat. As per the guidebook, the main purposes of this steam are to: [4P2CEM046]

a) Raise tower pressure so that lighter fractions condense

- b) Supply most heat needed to boil the crude
- c) Condense overhead vapours before they reach the condenser

d) Lower hydrocarbon partial pressures and cut coke formation

Correct answer: (d) Lower hydrocarbon partial pressures and cut coke formation.

The guidebook describes distillation towers under heat exchanger applications. A furnace heats crude oil above about 370 °C; as the volatile components boil off and rise up the tower they are cooled and condensed, and separation relies on differences in the boiling points of the hydrocarbon components. Steam is injected into the bottom of these towers to reduce the partial pressures of the hydrocarbons, which helps their separation at lower temperature, and to reduce coke formation on the tray tower.

Lower partial pressure means components vaporise at a lower temperature, so less furnace duty and less thermal cracking are needed. The steam is later condensed with the overhead product and separated as water.

Why not the others: (a) the steam lowers partial pressure; it does not raise tower pressure. (b) the fired furnace supplies the main heat, not the stripping steam. (c) overhead condensation is done in the condenser by the cooling medium.

Ref: BEE Guidebook Paper 2, Ch. 9 (Heat exchanger types by application: distillation towers).

Chapter 9: Heat Exchangers | Why steam is injected into distillation towers

47. A shell-and-tube exchanger will recover heat from low-pressure flash vapour (which condenses) into high-pressure boiler feed water. Which allocation follows the guidebook's design logic? [4P2CEM047]

- a) Vapour in the tubes, as condensation is most stable inside tubes
- b) Feed water in the tubes, vapour condensing on the shell side**
- c) Feed water on the shell side, as the shell is stronger than tubes
- d) Either side works, since baffles equalise shell and tube pressure

Correct answer: (b) Feed water in the tubes, vapour condensing on the shell side.

The guidebook explains that a shell-and-tube exchanger is used when both fluids are liquids or vapours under pressure, because both paths must be sealed. The shell is inherently weaker than the tubes, so the higher-pressure fluid is circulated in the tubes and the lower-pressure fluid flows through the shell. When a vapour carrying waste heat condenses, it is almost always placed in the shell, because condensing vapour inside small-diameter parallel tubes causes flow instabilities. Internal baffles in the shell direct the shell-side fluid over the tubes in multiple passes.

High-pressure feed water therefore goes in the tubes, with the low-pressure vapour condensing outside them.

Why not the others: (a) reverses the guidebook advice and invites flow instability. (c) wrongly calls the shell stronger than the tubes. (d) baffles guide flow; they do not equalise pressure between shell and tubes.

Ref: BEE Guidebook Paper 2, Ch. 8 (Shell and tube heat exchanger) and Ch. 9 (Heat exchanger types).

Chapter 9: Heat Exchangers | Fluid allocation in a shell-and-tube recovery exchanger

48. Select the statement about steam condensers that is consistent with the guidebook's description of heat exchangers by application: [4P2CEM048]

- a) Barometric condensers keep steam and cooling water separate
- b) Turbine condensers work above atmospheric pressure
- c) Ejector condensers cut motive steam by condensing vapour**
- d) Surface condensers mix cooling water directly with steam

Correct answer: (c) Ejector condensers cut motive steam by condensing vapour.

The guidebook explains that in steam ejector applications, condensers increase ejector effectiveness by condensing both the motive steam and the condensables pulled from the process, reducing the amount of motive steam required. In steam turbine applications, condensers typically operate under vacuum and remove a large amount of latent heat from exhaust steam, recovering it as condensate.

Condensers are of two types. Surface condensers circulate cooling water through tubes, giving a cool surface on which steam condenses; the condensate collects in a hotwell and is pumped to the return system. Barometric condensers rely on direct contact between cooling water and steam.

Why not the others: (a) describes surface condensers, not barometric ones. (b) turbine condensers operate under vacuum to increase the enthalpy drop. (d) describes barometric (direct-contact) condensers, not surface condensers.

Choosing the right type affects whether condensate can be recovered: only surface condensers return clean condensate.

Ref: BEE Guidebook Paper 2, Ch. 9 (Heat exchanger types by application: condensers).

Chapter 9: Heat Exchangers | Condensers in turbine and ejector service

49. A process duty of 4,00,000 kcal/h (≈ 465 kW) heats a cold stream from 40 °C to 80 °C with a hot stream cooling from 150 °C to 90 °C. The overall coefficient is 400 kcal/h (≈ 0.465 kW) m² °C. The vendor offers a 1-shell, 2-tube-pass exchanger, for which the chart gives $F = 0.88$. The heat transfer area required is about: [4P2CEM049]

a) 14.8 m²

b) 16.8 m²

c) 19.1 m²

d) 24.0 m²

Correct answer: (c) 19.1 m².

Given: $Q = 4,00,000$ kcal/h (≈ 465 kW); $U = 400$ kcal/h (≈ 0.465 kW) m² °C; hot 150 → 90 °C; cold 40 → 80 °C; $F = 0.88$.

Formula: $LMTD$ (counter-current) = $(\Delta T_1 - \Delta T_2)/\ln(\Delta T_1/\Delta T_2)$; $A = Q/(U \times F \times LMTD)$.

Substitution: $\Delta T_1 = 150 - 80 = 70$; $\Delta T_2 = 90 - 40 = 50$; $LMTD = 20/\ln(1.4) = 59.4$ °C; $A = 4,00,000/(400 \times 0.88 \times 59.4) = 19.1$ m².

Result: **Area ≈ 19.1 m²**, about 14% more than pure counter flow. The guidebook says F corrects the $LMTD$ for exchangers lacking true counter-current flow and usually lies between 0.85 and 0.98.

Why not the others: (b) 16.8 m² leaves out F , valid only for pure counter flow. (a) 14.8 m² multiplies the area by F instead of dividing. (d) 24.0 m² uses parallel-flow end differences (110 and 10 °C), which is not how a 1-2 exchanger is rated.

Ref: BEE Guidebook Paper 2, Ch. 9 (The temperature correction factor, F).

Chapter 9: Heat Exchangers | Area penalty from the LMTD correction factor

50. A shell-and-tube cooler needs 58 m² of outside tube area using 3 m long tubes of 19.05 mm OD and 16 mm ID. Cooling water at 90 m³/h flows inside the tubes, and the designer wants 1.5 m/s tube-side velocity. Which tube arrangement meets both conditions? [4P2CEM050]

a) 4 passes of 83 tubes

b) 5 passes of 83 tubes

c) 6 passes of 59 tubes

d) 7 passes of 59 tubes

Correct answer: (a) 4 passes of 83 tubes.

Given: $A = 58$ m² (outside); $L = 3$ m; OD 19.05 mm; ID 16 mm; water 90 m³/h = 0.025 m³/s; $v = 1.5$ m/s.

Formula: Tubes per pass = $\text{flow}/(v \times \pi \times ID^2/4)$; total tubes = $A/(\pi \times OD \times L)$; passes = total/tubes per pass.

Substitution: flow area per tube = 2.01×10^{-4} m²; tubes per pass = $0.025/(1.5 \times 2.01 \times 10^{-4}) = 82.9$, so 83; total = $58/(\pi \times 0.01905 \times 3) = 323$; passes = $323/83 = 3.9$, so 4.

Result: **4 passes of 83 tubes** (332 tubes). More passes raise velocity and film coefficient, at the cost of pumping power.

Why not the others: (b) uses the inside diameter for the outside area, giving 385 tubes. (c) uses the outside diameter for flow area, giving 59 tubes per pass. (d) makes both diameter errors.

Ref: BEE Guidebook Paper 2, Ch. 9 (Shell and tube heat exchangers; heat exchanger equation).

Chapter 9: Heat Exchangers | Tube passes for a cooling-water heat exchanger

..... End of Section I

Section – II: SHORT DESCRIPTIVE QUESTIONS**Marks: 8 x 5 = 40**

- (i) Answer all Eight questions
- (ii) Each question carries Five marks

S-1 [4P2CEM051 | Chapter 1: Fuels and Combustion | Coal stockyard losses: oxidation, wind and carpet loss]

A cement grinding unit receives 60,000 t/yr of coal (₹ 6,500 per tonne) and stacks it on bare earth in an open yard. A stock audit estimates the following losses as a share of coal received. Management is considering concrete storage bays on a hard base, compaction of heaps, first-in-first-out issue and a partial shed, costing ₹ 1.5 crore.

Loss	Present	After improvement
Wind loss	0.8%	0.3%
Carpet loss	1.5%	0.2%
Oxidation (heat value lost)	1.0%	0.5%

- a) Calculate the present annual loss in tonnes of coal-equivalent and in ₹, using the guidebook statement on the effect of oxidation. (2 Marks)
- b) Calculate the loss after improvement and the annual saving. (1.5 Marks)
- c) Calculate the simple payback. (1 Mark)
- d) What causes carpet loss and spontaneous combustion, and which guidebook measures reduce them? (0.5 Mark)

S-1 Ans (model answer with marking scheme)

Given: Receipts $R = 60,000$ t/yr; price ₹ 6,500/t; present losses wind 0.8%, carpet 1.5%, oxidation 1.0%; after: 0.3%, 0.2%, 0.5%; investment ₹ 1,50,00,000.

a) Present loss (2 marks)

Formula: Material lost = $R \times (\text{wind \%} + \text{carpet \%})$; the guidebook states that 1% oxidation has the same effect as 1% ash, so oxidation % is taken as an equal % loss of heat value, i.e. coal-equivalent = $R \times \text{oxidation \%}$

Substitution: material = $60,000 \times 2.3\% = 1,380$ t [0.5 mark]; oxidation equivalent = $60,000 \times 1\% = 600$ t [0.5 mark]; total = 1,980 t; ₹ = $1,980 \times 6,500$

Result: **Present loss $\approx 1,980$ t coal-equivalent $\approx ₹ 1,28,70,000$ (₹ 1.29 crore) per year** [1 mark]

b) Loss after improvement and saving (1.5 marks)

Formula: Loss = $R \times (0.3 + 0.2 + 0.5)\%$; saving = present – new

Substitution: new = $60,000 \times 1.0\% = 600$ t = ₹ 39,00,000 [0.5 mark]; saving = $1,980 - 600 = 1,380$ t; $1,380 \times 6,500$

Result: **Saving $\approx 1,380$ t/yr $\approx ₹ 89.7$ lakh per year** [1 mark]

c) Payback (1 mark)

Formula: Payback = investment/annual saving

Substitution: $1,50,00,000/89,70,000$

Result: **Simple payback ≈ 1.67 years (about 20 months)** [1 mark]

d) Causes and measures (0.5 mark)

Carpet loss is coal mixed with soil and dust into a soft bottom layer that cannot be recovered; spontaneous combustion follows gradual temperature build-up from oxidation inside the heap. The guidebook recommends a hard ground for stacking and standard storage bays of concrete and brick, and minimal handling to avoid generating fines; compaction and FIFO issue limit oxidation. [0.5 mark]

Marking note: $\pm 1\%$ tolerance; award full method marks if oxidation is valued as an equivalent heat loss; deduct $\frac{1}{2}$ mark if oxidation is ignored.

S-2 [4P2CEM052 | Chapter 3: Steam System | Warm-up condensate load of a steam main and drain trap sizing]

A new 300 m long, 150 mm steam main (pipe mass 28 kg/m, C_p of steel 0.12 kcal/kg °C (≈ 0.502 kJ/kg·K)) will be brought from 30 °C to saturation at 7 kg/cm²(g) (170 °C, hfg 489.46 kcal/kg ($\approx 2,049$ kJ/kg)) in 20 minutes at every Monday start-up. When running, the insulated main loses 120 kcal/h (≈ 0.140 kW) per metre. Drain points are to be provided at the guidebook spacing of about every 40 m, including the end of the main.

- Calculate the condensate formed while warming the pipe metal, and the average warm-up condensate rate. (2 Marks)
- Calculate the running condensate load of the main. (1 Mark)
- Find the number of drain points and the load per drain trap for warm-up (with a safety factor of 2) and for running. (1.5 Marks)
- What does the result imply for trap selection and start-up practice? (0.5 Mark)

S-2 Ans (model answer with marking scheme)

Given: $L = 300$ m; 28 kg/m; $C_p = 0.12$ kcal/kg °C (≈ 0.502 kJ/kg·K); $30 \rightarrow 170$ °C; hfg = 489.46 kcal/kg ($\approx 2,049$ kJ/kg); warm-up 20 min; running loss 120 kcal/h (≈ 0.140 kW)·m; drains every 40 m.

a) Warm-up condensate (2 marks)

Formula: Heat = pipe mass $\times C_p \times \Delta t$; condensate = heat/hfg; rate = condensate/warm-up time

Substitution: mass = $300 \times 28 = 8,400$ kg; heat = $8,400 \times 0.12 \times 140 = 1,41,120$ kcal [1 mark]; condensate = $1,41,120/489.46 = 288.3$ kg; rate = $288.3/(20/60)$

Result: **Warm-up condensate ≈ 288 kg, i.e. about 865 kg/h during the 20-minute warm-up** [1 mark]

b) Running load (1 mark)

Formula: Running condensate = $L \times \text{loss per metre/hfg}$

Substitution: $300 \times 120 = 36,000$ kcal/h; $36,000/489.46$

Result: **Running load ≈ 73.6 kg/h** [1 mark]

c) Drain points and trap loads (1.5 marks)

Formula: Number of drains = $L/\text{spacing}$ (rounded up); load per trap = total rate/number of drains

Substitution: $300/40 = 7.5 \rightarrow 8$ drain points [0.5 mark]; warm-up per trap = $865/8 = 108.1$ kg/h; $\times 2 = 216$ kg/h; running per trap = $73.6/8 = 9.2$ kg/h

Result: **8 drains; each trap must pass about 216 kg/h at start-up but only about 9 kg/h when running** [1 mark]

d) Implication (0.5 mark)

The start-up load is roughly 12 times the running load, so traps must be sized on warm-up load at the low start-up pressure difference, with proper drain pockets of full bore at each point; alternatively, supervised start-up with manual drain valves and slow warm-up avoids water hammer and allows smaller traps. [0.5 mark]

Marking note: $\pm 2\%$ tolerance; accept 7 or 8 drains if reasoning is shown; method marks for the sensible-heat-of-metal step.

S-3 [4P2CEM053 | Chapter 4: Furnaces | Scale loss in a reheating furnace: metal and fuel value of air–fuel ratio control]

A pusher-type reheating furnace heats 1,20,000 t/yr of billets (₹ 42,000 per tonne). It runs with about 60% excess air and frequent flame impingement on the stock; the audit puts scale loss (iron converted to oxide) at 2.0% of charged weight. An automatic air–fuel ratio control system with O₂ trim and re-aimed burners, costing ₹ 2.5 crore, is

expected to cut scale loss to 1.4% and specific oil consumption from 48 to 41 kg per tonne charged (oil ₹ 52,000 per tonne). The scale is mainly FeO (Fe 56, O 16) and is sold to a sinter plant at ₹ 1,500 per tonne.

- a) Calculate the iron lost and the scale generated per year, before and after. (1.5 Marks)
- b) Calculate the net annual value of the metal saved. (1.5 Marks)
- c) Calculate the annual fuel saving in ₹ and the share of the total benefit that comes from lower scale loss. (1 Mark)
- d) Calculate the simple payback and name two furnace practices, other than excess air, that increase scale. (1 Mark)

S-3 Ans (model answer with marking scheme)

Given: Charge 1,20,000 t/yr; scale loss 2.0% → 1.4%; billet ₹ 42,000/t; scale credit ₹ 1,500/t; FeO factor 72/56; SFC 48 → 41 kg/t; oil ₹ 52,000/t; investment ₹ 2,50,00,000.

a) Iron lost and scale formed (1.5 marks)

Formula: Iron lost = charge × scale loss %; scale mass = iron lost × 72/56 (FeO)

Substitution: before = $1,20,000 \times 0.020 = 2,400$ t Fe; after = $1,20,000 \times 0.014 = 1,680$ t Fe [0.5 mark]; scale = $2,400 \times 1.286 = 3,086$ t and $1,680 \times 1.286 = 2,160$ t [0.5 mark]

Result: **Iron saved = 720 t/yr; scale reduced by ≈ 926 t/yr** [0.5 mark]

b) Net value of metal saved (1.5 marks)

Formula: Net = iron saved × billet price – scale reduction × scale credit

Substitution: $720 \times 42,000 = ₹ 3,02,40,000$ [0.5 mark]; scale credit lost = $926 \times 1,500 = ₹ 13,88,571$ [0.5 mark]; net = $3,02,40,000 - 13,88,571$

Result: **Net metal benefit ≈ ₹ 2.89 crore per year** [0.5 mark]

Note: valuing the 926 t of scale at the billet price (₹ 3.89 crore) is a common error; the extra oxygen in the scale is not lost steel.

c) Fuel saving and share (1 mark)

Substitution: oil saved = $1,20,000 \times (48 - 41)/1,000 = 840$ t × ₹ 52,000 = ₹ 4.37 crore; total = $2.89 + 4.37 = ₹ 7.25$ crore; share = $2.89/7.25$

Result: **Fuel saving ≈ ₹ 4.37 crore/yr; scale reduction gives ≈ 40% of the total benefit**, which is why the guidebook calls excess-air scale loss 'equally a big loss in terms of money'. [1 mark]

d) Payback and other causes (1 mark)

Substitution: payback = $2.5/7.25 = 0.34$ year (about 4 months) [0.5 mark]

Result: **Payback ≈ 0.34 year**. Other causes of scale: flame impingement on the stock, overheating above the required temperature and long residence (soaking) time. [0.5 mark]

Marking note: ±2% tolerance; award full marks in (b) only if the student converts scale to iron (or states iron lost directly).

S-4 [4P2CEM054 | Chapter 5: Insulation and Refractories | Thermal expansion allowance in a refractory furnace wall]

A 14.4 m long straight side wall of a reheating furnace is being relined with high-alumina brick, laid at 30 °C. In service the hot face reaches 1,300 °C and the cold face of the brick about 300 °C, with a near-linear temperature profile. Mean coefficient of reversible linear expansion of the brick: 6.4×10^{-6} per °C. Expansion joints are 10 mm wide and filled with ceramic fibre paper that compresses to 25% of its thickness. Elastic modulus of the brick at temperature: 25,000 N/mm²; hot crushing strength: 60 N/mm².

- a) Calculate the mean brick temperature and the free expansion of the wall. (1.5 Marks)
- b) Calculate the number of expansion joints and their spacing. (1.5 Marks)

- c) A draftsman sized the joints using the hot-face temperature. How many joints would he provide, and what is the consequence? (1 Mark)
- d) Calculate the compressive stress if the wall had no joints and were fully restrained, and name the refractory property involved. (1 Mark)

S-4 Ans (model answer with marking scheme)

Given: $L = 14,400 \text{ mm}$; $\alpha = 6.4 \times 10^{-6} / ^\circ\text{C}$; laying 30°C ; hot face $1,300^\circ\text{C}$, cold face 300°C ; joint 10 mm , of which 75% (7.5 mm) can close; $E = 25,000 \text{ N/mm}^2$; crushing strength 60 N/mm^2 .

a) Free expansion (1.5 marks)

Formula: $T_{\text{mean}} = (T_{\text{hot}} + T_{\text{cold}})/2$; $\Delta L = \alpha \times L \times (T_{\text{mean}} - T_{\text{laying}})$

Substitution: $T_{\text{mean}} = (1,300 + 300)/2 = 800^\circ\text{C}$; $\Delta T = 800 - 30 = 770^\circ\text{C}$ [0.5 mark]; $\Delta L = 6.4 \times 10^{-6} \times 14,400 \times 770$ [0.5 mark]

Result: **Mean brick temperature 800°C ; free expansion $\approx 71.0 \text{ mm}$** [0.5 mark]

b) Joints (1.5 marks)

Formula: Number = $\Delta L / (\text{usable closure per joint})$, rounded up; spacing = L / number

Substitution: closure per joint = $10 \times 0.75 = 7.5 \text{ mm}$ [0.5 mark]; $70.96/7.5 = 9.46 \rightarrow 10 \text{ joints}$ [0.5 mark]; spacing = $14.4/10$

Result: **10 joints of 10 mm, one every $\approx 1.44 \text{ m}$** [0.5 mark]

c) Hot-face basis (1 mark)

Substitution: $\Delta L = 6.4 \times 10^{-6} \times 14,400 \times (1,300 - 30) = 117.0 \text{ mm}$; $117.0/7.5 = 15.6 \rightarrow 16 \text{ joints}$

Result: **16 joints:** they never close in service, leaving open gaps through which hot gas reaches the back-up insulation and shell, causing hot spots, heat loss and a weaker wall. [1 mark]

d) Restrained stress (1 mark)

Formula: $\sigma = E \times \alpha \times \Delta T$

Substitution: $25,000 \times 6.4 \times 10^{-6} \times 770 = 123.2 \text{ N/mm}^2$, about 2 times the 60 N/mm^2 hot crushing strength [0.5 mark]

Result: **$\approx 123 \text{ N/mm}^2$:** the hot face would crush, spall and bulge. The property is reversible thermal expansion, which the guidebook lists with volume stability as a key selection property for refractories. [0.5 mark]

Marking note: $\pm 2\%$ tolerance; method marks if the student uses mean temperature correctly; 9 joints acceptable only if the student shows $7.5 \text{ mm} \times 9 \geq \Delta L$ with a smaller ΔL from a stated assumption.

S-5 [4P2CEM055 | Chapter 6: FBC Boilers | Switching an AFBC boiler from under-bed to over-bed coal feeding]

A 25 TPH AFBC boiler burns 4.5 t/h of coal with under-bed pneumatic feeding of 1–6 mm coal. The feed pipes choke often, and it is proposed to change to over-bed spreader feeding of 6–10 mm coal. Trials at a sister plant show that, because more fines now burn above the bed, the boiler's combustion efficiency falls from 98.5% to 97.9%, all other losses unchanged.

Parameter	Under-bed (present)	Over-bed (proposed)
Crusher specific energy	4.0 kWh/t	2.2 kWh/t
Feeding system power	45 kW (transport air blower)	8 kW (screw + spreader)

Take 7,500 h/yr, power at ₹ 8/kWh and coal at ₹ 6,000 per tonne.

- a) Calculate the reduction in crusher and feeding power, and the annual electricity saving. (1.5 Marks)
- b) Calculate the extra coal needed because of the lower combustion efficiency, and its annual cost. (1.5 Marks)

c) Calculate the net annual effect. (1 Mark)

d) Give your recommendation, quoting the guidebook features of the two feeding systems. (1 Mark)

S-5 Ans (model answer with marking scheme)

Given: Coal 4.5 t/h; crusher 4.0 → 2.2 kWh/t; feeding 45 → 8 kW; combustion efficiency 98.5% → 97.9%; 7,500 h; ₹ 8/kWh; ₹ 6,000/t coal.

a) Electricity saving (1.5 marks)

Formula: Crusher saving = Δ specific energy $\times$ coal rate; feeding saving = difference in drive power

Substitution: crusher = $(4.0 - 2.2) \times 4.5 = 8.1$ kW [0.5 mark]; feeding = $45 - 8 = 37$ kW; total 45.1 kW $\times 7,500 = 3,38,250$ kWh [0.5 mark]; $\times ₹ 8$

Result: **Power saving ≈ 45.1 kW ≈ 3.38 lakh kWh $\approx ₹ 27.1$ lakh/yr** [0.5 mark]

b) Coal penalty (1.5 marks)

Formula: Coal needed $\propto 1/\text{efficiency}$, so new coal = present coal $\times$ (old efficiency/new efficiency)

Substitution: $4,500 \times 98.5/97.9 = 4,527.6$ kg/h; extra = 27.6 kg/h [1 mark]; $\times 7,500 = 206.8$ t $\times ₹ 6,000$

Result: **Extra coal ≈ 207 t/yr $\approx ₹ 12.4$ lakh/yr** [0.5 mark]

Note: subtracting the efficiency points directly (0.6% of 4.5 t/h) gives a similar figure here but is not the correct relation.

c) Net effect (1 mark)

Substitution: $27.06 - 12.41 = ₹ 14.65$ lakh/yr

Result: **Net gain $\approx ₹ 14.6$ lakh/yr** [1 mark]

d) Recommendation (1 mark)

Adopt over-bed feeding. The guidebook notes that under-bed pneumatic feeding needs coal crushed to 1–6 mm and transport lines that can choke with bed material, while over-bed spreader feeding of 6–10 mm coal accepts oversize fuel and eliminates transport lines. Keep a watch on fines and on carbon carry-over through secondary air and fines control. [1 mark]

Marking note: $\pm 2\%$ tolerance; a student who ignores the efficiency penalty and reports ₹ 27 lakh loses the marks for (b) and (c).

S-6 [4P2CEM056 | Chapter 7: Cogeneration | Marginal cost of extra extraction steam from an extraction-condensing turbine]

An extraction-condensing turbine takes 40 TPH of steam at 3,350 kJ/kg. Steam is extracted for process at 2,900 kJ/kg and the rest expands to the condenser at 2,350 kJ/kg; condensate leaves the condenser at 420 kJ/kg. Mechanical and generator efficiency together is 95%. Process demand rises from 20 TPH to 25 TPH of extraction steam with throttle flow unchanged. Grid power costs ₹ 7.50/kWh; steam from a separate boiler through a PRV would cost ₹ 2,300 per tonne.

a) Calculate the turbine output before and after the change. (2 Marks)

b) Calculate the power lost per tonne of extra extraction steam and its cost. (1 Mark)

c) Calculate the reduction in heat rejected in the condenser and compare the cost of extraction steam with boiler steam. (1.5 Marks)

d) Why is extraction steam so cheap at the margin? (0.5 Mark)

S-6 Ans (model answer with marking scheme)

Given: Throttle 40,000 kg/h at 3,350 kJ/kg; extraction 2,900 kJ/kg; exhaust 2,350 kJ/kg; condensate 420 kJ/kg; $\eta = 0.95$; extraction 20 → 25 TPH.

a) Power before and after (2 marks)

Formula: $P = [m_{\text{throttle}} \times (h_{\text{in}} - h_{\text{ext}}) + m_{\text{cond}} \times (h_{\text{ext}} - h_{\text{exh}})] \times \eta / 3,600$

Substitution: HP section = $40,000 \times 450 \times 0.95 / 3,600 = 4,750 \text{ kW}$; LP before = $20,000 \times 550 \times 0.95 / 3,600 = 2,902.8 \text{ kW}$ [1 mark]; LP after = $15,000 \times 550 \times 0.95 / 3,600 = 2,177.1 \text{ kW}$

Result: **Output before $\approx 7,653 \text{ kW}$; after $\approx 6,927 \text{ kW}$; loss $\approx 726 \text{ kW}$** [1 mark]

b) Marginal power per tonne (1 mark)

Substitution: $725.7 \text{ kW} / 5 \text{ t/h} = 145.1 \text{ kWh per tonne}$; $\times ₹ 7.50$

Result: **$\approx 145 \text{ kWh lost per tonne of extra extraction steam} \approx ₹ 1,089 \text{ per tonne}$** [1 mark]

c) Condenser and comparison (1.5 marks)

Formula: Condenser heat saved = $\Delta m \times (h_{\text{exh}} - h_{\text{condensate}}) / 3,600$

Substitution: $5,000 \times (2,350 - 420) / 3,600 = 2,680.6 \text{ kW}$ [0.5 mark]

Result: **Condenser rejection falls by $\approx 2,681 \text{ kW}$; extraction steam costs $\approx ₹ 1,089/\text{t}$ (lost power only, fuel unchanged) against $₹ 2,300/\text{t}$ for boiler/PRV steam, so extraction is the cheaper source** [1 mark]

d) Reason (0.5 mark)

With throttle flow fixed, fuel input is unchanged; the extra process steam is heat that would otherwise be thrown away as latent heat in the condenser, so only the small power from expansion below the extraction point is sacrificed. [0.5 mark]

Marking note: $\pm 2\%$ tolerance; method marks for separating HP and LP sections.

S-7 [4P2CEM057 | Chapter 8: Waste Heat Recovery | Dilution air ahead of a metallic recuperator]

A forging furnace burns 360 kg/h of furnace oil (GCV $10,000 \text{ kcal/kg}$ ($\approx 41,868 \text{ kJ/kg}$)). Its $6,000 \text{ kg/h}$ of flue gas leaves at $1,180^\circ\text{C}$ ($C_p 0.28 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 1.17 \text{ kJ/kg}\cdot\text{K}$)), but the metallic recuperator liner is limited to $1,000^\circ\text{C}$ inlet. Ambient air at 35°C ($C_p 0.26 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 1.09 \text{ kJ/kg}\cdot\text{K}$)) is used as dilution air. The recuperator then preheats $5,400 \text{ kg/h}$ of combustion air from 35°C to 450°C .

a) Calculate the dilution air needed. (1.5 Marks)

b) Calculate the heat recovered in the recuperator. (1 Mark)

c) Calculate the flue gas temperature leaving the recuperator (use the mixed-gas C_p). (1.5 Marks)

d) Estimate the fuel saving, assuming preheat displaces fuel heat one-for-one, and state one drawback of dilution. (1 Mark)

S-7 Ans (model answer with marking scheme)

Given: Flue gas $6,000 \text{ kg/h}$, $1,180^\circ\text{C}$, $C_p 0.28$; limit $1,000^\circ\text{C}$; air 35°C , $C_p 0.26$; combustion air $5,400 \text{ kg/h}$, $35 \rightarrow 450^\circ\text{C}$; oil 360 kg/h , GCV $10,000 \text{ kcal/kg}$ ($\approx 41,868 \text{ kJ/kg}$).

a) Dilution air (1.5 marks)

Formula: $m_g \times C_{p_g} \times (1,180 - 1,000) = m_a \times C_{p_a} \times (1,000 - 35)$

Substitution: $6,000 \times 0.28 \times 180 = 3,02,400 \text{ kcal/h}$ [0.5 mark]; $m_a = 3,02,400 / (0.26 \times 965)$

Result: **Dilution air $\approx 1,205 \text{ kg/h}$** [1 mark]

b) Heat recovered (1 mark)

Substitution: $5,400 \times 0.26 \times (450 - 35)$

Result: **$Q \approx 5,82,660 \text{ kcal/h}$ ($\approx 678 \text{ kW}$)** [1 mark]

c) Gas exit temperature (1.5 marks)

Formula: Mixed gas = $7,205 \text{ kg/h}$; $C_{p(\text{mix})} = (6,000 \times 0.28 + 1,205 \times 0.26) / 7,205$; $T_{\text{out}} = 1,000 - Q / (m \times C_p)$

Substitution: $C_{p(\text{mix})} = 0.2767$ [0.5 mark]; drop = $5,82,660 / (7,205 \times 0.2767) = 292.3^\circ\text{C}$

Result: **Gas leaves the recuperator at $\approx 708^\circ\text{C}$** [1 mark]

d) Fuel saving and drawback (1 mark)

Substitution: $5,82,660/10,000 = 58.3 \text{ kg/h}$; $58.3/360 \times 100$

Result: $\approx 58 \text{ kg/h oil}$, **about 16% of present firing**. Drawback: dilution raises gas volume and ID fan load and wastes some recoverable heat; staging or radiation recuperators are alternatives. [1 mark]

Marking note: $\pm 2\%$ tolerance; accept 0.28 for mixed C_p with a small deviation in exit temperature.

S-8 [4P2CEM058 | Chapter 8: Waste Heat Recovery | Using kiln cooling-zone air as spray dryer intake]

A ceramic plant's tunnel kiln cooling zone exhausts $14,000 \text{ Nm}^3/\text{h}$ of clean hot air at 230°C . Its spray dryer's natural gas hot air generator (efficiency 85%) heats the same quantity of ambient air from 35°C to 550°C . It is proposed to duct the kiln air to the dryer intake, arriving at 210°C . Data: air density 1.293 kg/Nm^3 , $C_p 0.24 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 1.00 \text{ kJ/kg}\cdot\text{K}$); gas GCV $9,000 \text{ kcal/Sm}^3$ ($\approx 37.7 \text{ MJ/Sm}^3$) at ₹ 45 per Sm^3 ; 7,000 h/yr; booster fan 30 kW at ₹ 8/kWh; ducting and fan ₹ 1.2 crore.

- a) Calculate the heat saved at the hot air generator. (1.5 Marks)
- b) Calculate the gas saved per hour and per year in ₹. (1.5 Marks)
- c) Calculate the net annual saving and simple payback. (1.5 Marks)
- d) State one precaution. (0.5 Mark)

S-8 Ans (model answer with marking scheme)

Given: $14,000 \text{ Nm}^3/\text{h}$; $\rho = 1.293 \text{ kg/Nm}^3$; $C_p = 0.24$; intake $35 \rightarrow 210^\circ\text{C}$; $\eta = 0.85$; GCV $9,000 \text{ kcal/Sm}^3$ ($\approx 37.7 \text{ MJ/Sm}^3$); ₹ 45/ Sm^3 ; 7,000 h; fan 30 kW at ₹ 8/kWh; investment ₹ 1,20,00,000.

a) Heat saved (1.5 marks)

Formula: $Q = m \times C_p \times (T_{\text{new intake}} - T_{\text{old intake}})$

Substitution: $m = 14,000 \times 1.293 = 18,102 \text{ kg/h}$ [0.5 mark]; $Q = 18,102 \times 0.24 \times 175$

Result: **$Q \approx 7,60,284 \text{ kcal/h}$ ($\approx 884 \text{ kW}$)** [1 mark]

b) Gas saving (1.5 marks)

Formula: $\text{Gas} = Q/(\eta \times \text{GCV})$

Substitution: $7,60,284/(0.85 \times 9,000) = 99.4 \text{ Sm}^3/\text{h}$ [0.5 mark]; $\times 45 \times 7,000$

Result: **$\approx 99.4 \text{ Sm}^3/\text{h} \approx ₹ 3.13 \text{ crore per year}$** [1 mark]

c) Net saving and payback (1.5 marks)

Substitution: fan = $30 \times 8 \times 7,000 = ₹ 16,80,000$; net = $3,13,05,812 - 16,80,000 = ₹ 2,96,25,812$ [0.5 mark];

payback = $1,20,00,000/2,96,25,812$

Result: **Net $\approx ₹ 2.96 \text{ crore/yr}$; payback $\approx 0.41 \text{ year}$ (about 5 months)** [1 mark]

d) Precaution (0.5 mark)

Ensure the kiln air is free of dust and kiln gases (no product contamination), and that kiln cooling is not disturbed when the dryer stops; provide a bypass damper and insulate the duct. [0.5 mark]

Marking note: $\pm 2\%$ tolerance.

..... End of Section II

Section – III: LONG DESCRIPTIVE QUESTIONS

Marks: 6 x 10 = 60

(i) Answer all Six questions

(ii) Each question carries Ten marks

L-1 [4P2CEM059 | Chapter 2: Boilers | Correcting gas and steam meter readings in a direct-method boiler test]

A natural gas fired boiler is tested by the direct method. The gas turbine meter reads 640 m³/h at the line condition of 2.0 kg/cm²(g) (≈ 1.96 bar(g)) and 35 °C (atmospheric pressure 1.033 kg/cm² (≈ 1.01 bar); reference 0 °C). The steam orifice meter shows 24,000 kg/h, but its density constant was set for 10.5 kg/cm²(g) (≈ 10.3 bar(g)) saturated steam (5.70 kg/m³), whereas the boiler now runs at 7 kg/cm²(g) (≈ 6.86 bar(g)) (4.03 kg/m³). Steam enthalpy is 661 kcal/kg ($\approx 2,767$ kJ/kg), feed water is at 102 °C, gas GCV is 9,200 kcal/Nm³ (≈ 38.5 MJ/Nm³), and the boiler runs 8,000 h/yr.

a) Correct the gas flow to Nm³/h. (2 Marks)

b) Correct the steam flow reading. (2.5 Marks)

c) Calculate the efficiency (i) with both raw readings, (ii) with only the gas corrected, (iii) with both corrected. Comment. (3 Marks)

d) Check the corrected evaporation ratio against the guidebook range for gas firing, and find the annual phantom steam that would be booked to users if the steam meter were not corrected. (2.5 Marks)

L-1 Ans (model answer with marking scheme)

Given: Gas 640 m³/h at 2.0 kg/cm²(g) (≈ 1.96 bar(g)), 35 °C; P_{atm} 1.033 kg/cm² (≈ 1.01 bar); steam indicated 24,000 kg/h; ρ_{design} 5.70, ρ_{actual} 4.03 kg/m³; h = 661 kcal/kg ($\approx 2,767$ kJ/kg); feed 102 °C; GCV 9,200 kcal/Nm³ (≈ 38.5 MJ/Nm³); 8,000 h/yr.

a) Gas flow correction (2 marks)

Formula: $V_N = V \times (P_{\text{abs}}/1.033) \times (273/T_{\text{abs}})$

Substitution: $P_{\text{abs}} = 2.0 + 1.033 = 3.033$ kg/cm²; $V_N = 640 \times (3.033/1.033) \times (273/308) = 640 \times 2.936 \times 0.886$ [1 mark]

Result: **Gas flow $\approx 1,665.6$ Nm³/h** [1 mark]

b) Steam flow correction (2.5 marks)

Formula: For a differential-pressure meter $m = Kv(\Delta P \times \rho)$; the meter computes with ρ_{design} , so true flow = indicated $\times \sqrt{\rho_{\text{actual}}/\rho_{\text{design}}}$

Substitution: $\sqrt{4.03/5.70} = \sqrt{0.7070} = 0.8408$ [1 mark]; $24,000 \times 0.8408$ [0.5 mark]

Result: **True steam flow $\approx 20,180$ kg/h** [1 mark]

c) Efficiencies (3 marks)

Formula: $\eta = \text{steam} \times (h - h_{\text{fw}})/(\text{gas} \times \text{GCV}) \times 100$, with $h - h_{\text{fw}} = 661 - 102 = 559$ kcal/kg

Substitution: (i) $24,000 \times 559/(640 \times 9,200) = 227.9\%$; (ii) $24,000 \times 559/(1,665.6 \times 9,200) = 87.6\%$ [1 mark]; (iii) $20,180 \times 559/(1,665.6 \times 9,200)$ [1 mark]

Result: **(i) $\approx 228\%$ (impossible); (ii) $\approx 87.6\%$ (still optimistic for a non-condensing gas boiler); (iii) $\approx 73.6\%$, the true efficiency.** Direct-method results are only as good as the flow measurements; both meters must be corrected to actual conditions. [1 mark]

d) Evaporation ratio and phantom steam (2.5 marks)

Formula: ER = steam/fuel; phantom steam = (indicated – true) $\times$ hours

Substitution: $ER = 20,180/1,665.6 = 12.1$ kg steam per Nm^3 [1 mark]; phantom = $(24,000 - 20,180) \times 8,000 = 3,819.8 \times 8,000$ kg [0.5 mark]

Result: **ER $\approx$ 12.1, inside the guidebook gas range of 11–13; about 30,560 t/yr of steam would be booked to users that was never generated**, distorting departmental costing and hiding the 73.6% efficiency. [1 mark]

Marking note: $\pm 1\%$ tolerance; award method marks for the square-root density correction even with slips in arithmetic.

L-2 [4P2CEM060 | Chapter 3: Steam System | Choosing the lowest practical steam pressure for a process heater]

A liquor heater raises 20,000 kg/h of liquor (C_p 0.9 kcal/kg $^{\circ}C$ (≈ 3.77 kJ/kg $\cdot K$)) from 40 $^{\circ}C$ to 90 $^{\circ}C$. It is now supplied with steam at 6 kg/cm ^{2} (g) (≈ 5.88 bar(g)) through a PRV from a boiler generating dry steam of enthalpy 663 kcal/kg ($\approx 2,776$ kJ/kg) (enthalpy unchanged through the PRV). Condensate leaves the heater at saturation and is drained (not returned); make-up water enters the boiler at 30 $^{\circ}C$. The heater has 22 m ^{2} of area with $U = 500$ kcal/h $\cdot m^2$ (≈ 582 W/m ^{2}) $\cdot^{\circ}C$. Oil-fired boiler: efficiency 84%, GCV 10,200 kcal/kg ($\approx 42,705$ kJ/kg), oil ₹ 52,000 per tonne; 6,000 h/yr.

Heater steam pressure kg/cm ^{2} (g)	Saturation temperature $^{\circ}C$	hf kcal/kg
6	164.2	165.67
4	151.8	152.13
2	132.9	133.42

- Calculate the steam consumption at 6 kg/cm ^{2} (g) (≈ 5.88 bar(g)). (2 Marks)
- Calculate the LMTD and the area needed at 6, 4 and 2 kg/cm ^{2} (g) (≈ 1.96 bar(g)), and state which pressures the existing heater can work at. (3 Marks)
- Calculate the annual oil and cost saving if the heater is run at the lowest feasible pressure with the existing area. (3 Marks)
- If 6 m ^{2} of area is added at ₹ 9 lakh, evaluate operation at 2 kg/cm ^{2} (g) (≈ 1.96 bar(g)). (2 Marks)

L-2 Ans (model answer with marking scheme)

Given: $Q = 20,000 \times 0.9 \times 50 = 9,00,000$ kcal/h ($\approx 1,047$ kW); steam 663 kcal/kg ($\approx 2,776$ kJ/kg); make-up 30 $^{\circ}C$; $A = 22$ m ^{2} ; $U = 500$; $\eta = 0.84$; GCV 10,200; ₹ 52/kg; 6,000 h/yr.

a) Steam at 6 kg/cm ^{2} (g) (≈ 5.88 bar(g)) (2 marks)

Formula: $Steam = Q/(h_{steam} - hf)$

Substitution: $9,00,000/(663 - 165.67) = 9,00,000/497.33$ [1 mark]

Result: **Steam $\approx$ 1,810 kg/h** [1 mark]

b) LMTD and area (3 marks)

Formula: $\Delta T_1 = T_s - 40$, $\Delta T_2 = T_s - 90$; $LMTD = (\Delta T_1 - \Delta T_2)/\ln(\Delta T_1/\Delta T_2)$; $A = Q/(U \times LMTD)$

Substitution: 6: $124.2/74.2 \rightarrow LMTD$ 97.1 $^{\circ}C$, $A = 18.5$ m ^{2} ; 4: $111.8/61.8 \rightarrow LMTD$ 84.3 $^{\circ}C$, $A = 21.3$ m ^{2} [1 mark]; 2: $92.9/42.9 \rightarrow LMTD$ 64.7 $^{\circ}C$, $A = 27.8$ m ^{2} [1 mark]

Result: **Existing 22 m ^{2} works at 6 and 4 kg/cm ^{2} (g) (≈ 3.92 bar(g)) but not at 2 kg/cm ^{2} (g) (≈ 1.96 bar(g))** [1 mark]

c) Saving at 4 kg/cm ^{2} (g) (≈ 3.92 bar(g)) (3 marks)

Formula: $Steam = Q/(663 - hf)$; boiler heat = steam $\times (663 - 30)$; oil = $\Delta heat/(\eta \times GCV)$

Substitution: steam at 4 = $9,00,000/510.87 = 1,761.7$ kg/h; $\Delta steam = 1,809.7 - 1,761.7 = 48.0$ kg/h [1 mark]; $\Delta heat = 48.0 \times 633 = 30,384$ kcal/h; oil = $30,384/(0.84 \times 10,200) = 3.55$ kg/h [1 mark]; $\times 6,000$ h = 21.3 t; $\times ₹ 52,000$

Result: **Oil saving $\approx$ 21.3 t/yr $\approx$ ₹ 11.1 lakh/yr, at no cost (PRV reset)** [1 mark]

d) Operation at 2 kg/cm ^{2} (g) (≈ 1.96 bar(g)) with added area (2 marks)

Substitution: steam = $9,00,000/529.58 = 1,699.5$ kg/h; Δ steam vs 6 = 110.2 kg/h; Δ heat = 69,757 kcal/h; oil = 8.14 kg/h $\rightarrow$ 48.9 t/yr = ₹ 25.4 lakh; extra over 4 kg/cm²(g) = ₹ 14.3 lakh/yr [1 mark]; payback of ₹ 9 lakh = 0.63 yr
 Result: **Adding 6 m² (28 m² total $\geq$ 27.8 m²) and running at 2 kg/cm²(g) ($\approx$ 1.96 bar(g)) pays back in $\approx$ 0.6 year.**
 The saving arises because condensate is drained at lower hf; returning the condensate would also cut this loss. [1 mark]

Marking note: $\pm 2\%$ tolerance on LMTD and area; accept the conclusion if consistent with the student's areas.

L-3 [4P2CEM061 | Chapter 4: Furnaces | Capacity utilisation of a batch annealing furnace]

An oil-fired bogie annealing furnace heats steel coils from 30 °C to 850 °C (mean Cp 0.16 kcal/kg °C ($\approx$ 0.670 kJ/kg·K)). Per cycle, the lining and bogie absorb a fixed 18 lakh kcal ($\approx$ 7,536 MJ) regardless of load, and the walls lose 1.5 lakh kcal/h ($\approx$ 174 kW). A cycle takes 14 h with a 6 t load and 16 h with a full 12 t load. Only 45% of fuel heat is available in the furnace after flue gas loss. Oil: GCV 10,200 kcal/kg ($\approx$ 42,705 kJ/kg), ₹ 52,000 per tonne. Annual throughput is 3,000 t.

- Calculate fuel per cycle, specific fuel consumption and efficiency with a 6 t load. (3 Marks)
- Repeat for a full 12 t load. (3 Marks)
- Calculate the annual oil and cost saving by always charging full loads. (2 Marks)
- Sand seals at the bogie–shell gap and a new door seal, costing ₹ 25 lakh, cut the wall and leakage loss from 1.5 to 1.1 lakh kcal/h ($\approx$ 128 kW). With full loads, calculate the further saving and payback. (2 Marks)

L-3 Ans (model answer with marking scheme)

Given: Cp 0.16; $\Delta t = 820$ °C; stored heat 18,00,000 kcal/cycle; wall loss 1,50,000 kcal/h ($\approx$ 174 kW); cycle 14 h (6 t) and 16 h (12 t); available heat 45%; GCV 10,200; ₹ 52,000/t; 3,000 t/yr.

a) 6 t load (3 marks)

Formula: Heat needed = load heat + stored heat + wall loss $\times$ hours; fuel = heat/(available heat $\times$ GCV); η = load heat/(fuel $\times$ GCV)

Substitution: load = $6,000 \times 0.16 \times 820 = 7,87,200$ kcal; wall = $1,50,000 \times 14 = 21,00,000$ kcal; total = 46,87,200 kcal [1 mark]; fuel = $46,87,200/(0.45 \times 10,200) = 1,021.2$ kg [1 mark]

Result: $\approx$ **1,021 kg/cycle; SFC $\approx$ 170.2 kg/t; efficiency $\approx$ 7.6%** [1 mark]

b) 12 t load (3 marks)

Substitution: load = $12,000 \times 0.16 \times 820 = 15,74,400$ kcal; wall = $1,50,000 \times 16 = 24,00,000$ kcal; total = 57,74,400 kcal [1 mark]; fuel = $57,74,400/4,590 = 1,258.0$ kg [1 mark]

Result: $\approx$ **1,258 kg/cycle; SFC $\approx$ 104.8 kg/t; efficiency $\approx$ 12.3%** [1 mark]

c) Annual saving (2 marks)

Substitution: 6 t loads: $500 \text{ cycles} \times 1,021.2 = 510.6$ t; 12 t loads: $250 \times 1,258.0 = 314.5$ t [1 mark]; saving = 196.1 t $\times$ ₹ 52,000

Result: **Saving $\approx$ 196 t oil $\approx$ ₹ 1.02 crore per year, with no investment** — fixed losses are spread over twice the output. [1 mark]

d) Bogie and door sealing (2 marks)

Substitution: loss = $1,10,000 \times 16 = 17,60,000$ kcal; total = $15,74,400 + 18,00,000 + 17,60,000 = 51,34,400$ kcal; fuel = $51,34,400/4,590 = 1,118.6$ kg/cycle; saving = $(1,258.0 - 1,118.6) \times 250 = 34.9$ t = ₹ 18.1 lakh [1 mark]; payback = 25/18.1

Result: **Further saving $\approx$ 35 t/yr $\approx$ ₹ 18.1 lakh; payback $\approx$ 1.4 years.** Loading first, then hardware: the guidebook notes bogie furnaces lose heat through inadequate sealing of the gap between bogies and shell. [1 mark]

Marking note: $\pm 2\%$ tolerance; accept SFC per tonne of load in kg/t.

A textile processing unit in Gujarat runs a natural-gas gas turbine cogeneration plant rated 5,000 kW at ISO conditions (15 °C) with a heat rate of 3,000 kcal/kWh ($\approx 12,560$ kJ/kWh) (NCV basis). Its exhaust feeds an unfired HRSG. The manufacturer's correction curves give, for every °C of compressor inlet temperature above 15 °C, a 0.7% drop in output and a 0.25% rise in heat rate. For 3,000 h of summer the ambient is 40 °C. An evaporative inlet air cooler costing ₹ 55 lakh would bring the inlet air to 26 °C.

Data	Value
Gas NCV / price	8,500 kcal/Sm ³ (≈ 35.6 MJ/Sm ³) / ₹ 30 per Sm ³
Grid power displaced	₹ 9.50/kWh
Air flow / humid specific heat	19 kg/s / 1.02 kJ/kg·K
Latent heat of water / bleed allowance	2,450 kJ/kg / 30% over evaporation
Water cost	₹ 60/m ³
HRSG recovery of extra exhaust heat; gas-fired boiler efficiency	60%; 90%

- Calculate the output and heat rate at 40 °C and at 26 °C inlet. (3 Marks)
- Calculate the extra gas burnt and the incremental heat rate of the extra power. (2 Marks)
- Calculate the water make-up of the cooler. (1 Mark)
- Calculate the net annual benefit and payback (i) on power alone and (ii) crediting the extra HRSG steam that displaces a gas-fired boiler. (3 Marks)
- Why is a gas turbine more sensitive to ambient temperature than a reciprocating engine? (1 Mark)

L-4 Ans (model answer with marking scheme)

Given: ISO 5,000 kW, 3,000 kcal/kWh ($\approx 12,560$ kJ/kWh); -0.7% output and $+0.25\%$ heat rate per °C above 15 °C; 40 °C $\rightarrow$ 26 °C; 3,000 h; gas 8,500 kcal/Sm³ (≈ 35.6 MJ/Sm³) at ₹ 30; grid ₹ 9.50/kWh; cooler ₹ 55,00,000.

a) Derated performance (3 marks)

Formula: $P = P_{\text{ISO}} \times (1 - 0.007 \times \Delta T)$; $HR = HR_{\text{ISO}} \times (1 + 0.0025 \times \Delta T)$, $\Delta T = T_{\text{inlet}} - 15$

Substitution: 40 °C: $\Delta T = 25$; $P = 5,000 \times 0.825 = 4,125$ kW; $HR = 3,000 \times 1.0625 = 3,187.5$ kcal/kWh [1.5 marks];

26 °C: $\Delta T = 11$; $P = 5,000 \times 0.923 = 4,615$ kW; $HR = 3,000 \times 1.0275 = 3,082.5$ kcal/kWh [1 mark]

Result: **Cooling recovers 490 kW and cuts heat rate by 105 kcal/kWh (≈ 440 kJ/kWh)** [0.5 mark]

b) Extra gas and incremental heat rate (2 marks)

Formula: Fuel = $P \times HR$; incremental $HR = \Delta \text{Fuel} / \Delta P$

Substitution: $4,125 \times 3,187.5 = 1,31,48,438$ kcal/h; $4,615 \times 3,082.5 = 1,42,25,738$ kcal/h; $\Delta = 10,77,300$ kcal/h [1 mark]; $10,77,300/490$

Result: **Extra fuel ≈ 10.77 lakh kcal/h ($\approx 1,252$ kW) (≈ 127 Sm³/h); incremental heat rate $\approx 2,199$ kcal/kWh ($\approx 9,207$ kJ/kWh), lower than the machine's own heat rate because the extra output comes from denser air.** [1 mark]

c) Water make-up (1 mark)

Substitution: evaporation = $19 \times 1.02 \times (40 - 26)/2,450 = 0.1107$ kg/s = 398.7 kg/h; make-up = $398.7 \times 1.3 = 518$ kg/h; $\times 3,000$ h = $1,555$ m³ $\times$ ₹ 60

Result: **Make-up ≈ 518 kg/h ($\approx 1,555$ m³ per summer, $\approx$ ₹ 0.93 lakh)** [1 mark]

d) Economics (3 marks)

Substitution (i): power value = $490 \times 3,000 \times 9.50 = ₹ 1,39,65,000$; gas = $10,77,300 \times 3,000/8,500 = 3,80,224 \text{ Sm}^3$
 $\times ₹ 30 = ₹ 1,14,06,706$ [1 mark]; net = $1,39,65,000 - 1,14,06,706 - 93,290 = ₹ 24,65,004$; payback = $55/24.65 = 2.2$ years [1 mark]

Substitution (ii): extra exhaust heat = $10,77,300 - 490 \times 860 = 6,55,900 \text{ kcal/h}$; recovered = $0.60 \times 6,55,900 = 3,93,540 \text{ kcal/h}$; boiler gas saved = $3,93,540/(0.90 \times 8,500) \times 3,000 = 1,54,329 \text{ Sm}^3 = ₹ 46,29,882$; net = ₹ 70,94,887; payback = $55/70.95$

Result: **(i) $\approx ₹ 24.7$ lakh/yr, payback ≈ 2.2 years; (ii) $\approx ₹ 70.9$ lakh/yr, payback ≈ 0.78 year** — in cogeneration the exhaust heat credit decides the case. [1 mark]

e) Ambient sensitivity (1 mark)

A gas turbine compressor handles a nearly fixed volume of air, so hotter, less dense air means less mass flow, more compressor work per kg and less net output. The guidebook notes reciprocating engines are not as sensitive to ambient temperature as gas turbines. [1 mark]

Marking note: $\pm 1\%$ tolerance; accept results using rounded gas flow; deduct 1 mark in (d) if the HRSG credit is added at gas price without dividing by boiler efficiency.

L-5 [4P2CEM063 | Chapter 8: Waste Heat Recovery | Incinerating a combustible process off-gas with heat recovery]

A chemical plant vents $6,000 \text{ Nm}^3/\text{h}$ of off-gas containing 14% CO and 6% H₂ by volume (rest N₂, CO₂ and moisture) through a flare stack. It is proposed to burn it in an incinerator with a waste heat boiler producing steam of 665 kcal/kg ($\approx 2,784 \text{ kJ/kg}$) from feed water at 105 °C. Net heating values: CO $3,020 \text{ kcal/Nm}^3$ ($\approx 12.6 \text{ MJ/Nm}^3$); H₂ $2,570 \text{ kcal/Nm}^3$ ($\approx 10.8 \text{ MJ/Nm}^3$). Incinerator plus boiler efficiency on heat released: 72%. Excess air 20%. Steam will displace steam from a coal-fired boiler (efficiency 78%, GCV $4,200 \text{ kcal/kg}$ ($\approx 17,585 \text{ kJ/kg}$), ₹ 6,500 per tonne). Operation 8,000 h/yr; project cost ₹ 6 crore. CO density 1.25 kg/Nm^3 .

- Calculate the heating value of the off-gas and the heat released. (2 Marks)
- Calculate the combustion air required. (2 Marks)
- Calculate the steam generated. (2 Marks)
- Calculate the coal and cost saved and the simple payback. (3 Marks)
- Calculate the CO destroyed per hour and state the dual benefit noted in the guidebook. (1 Mark)

L-5 Ans (model answer with marking scheme)

Given: $6,000 \text{ Nm}^3/\text{h}$; CO 0.14, H₂ 0.06; NCV CO $3,020$, H₂ $2,570 \text{ kcal/Nm}^3$ ($\approx 10.8 \text{ MJ/Nm}^3$); $\eta = 0.72$; EA 20%; steam 665, feed 105 kcal/kg ($\approx 440 \text{ kJ/kg}$); coal boiler 0.78, $4,200 \text{ kcal/kg}$ ($\approx 17,585 \text{ kJ/kg}$), ₹ 6,500/t; 8,000 h; ₹ 6,00,00,000.

a) Heating value and heat released (2 marks)

Formula: $HV = \sum \text{fraction} \times NCV$; $Q = \text{flow} \times HV$

Substitution: $0.14 \times 3,020 + 0.06 \times 2,570 = 422.8 + 154.2 = 577.0 \text{ kcal/Nm}^3$ [1 mark]; $Q = 6,000 \times 577$

Result: **HV $\approx 577 \text{ kcal/Nm}^3$ ($\approx 2.42 \text{ MJ/Nm}^3$); heat released $\approx 34,62,000 \text{ kcal/h}$ ($\approx 4,026 \text{ kW}$)** [1 mark]

b) Combustion air (2 marks)

Formula: $\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2$; $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$; $\text{O}_2 = 0.5 \times (\text{CO} + \text{H}_2)$; $\text{air} = \text{O}_2/0.21 \times (1 + \text{EA})$

Substitution: $\text{O}_2 = 0.5 \times 0.20 = 0.10 \text{ Nm}^3/\text{Nm}^3$; theoretical air = $0.476 \text{ Nm}^3/\text{Nm}^3$ [1 mark]; actual = $0.476 \times 1.2 \times 6,000$

Result: **Combustion air $\approx 3,429 \text{ Nm}^3/\text{h}$** [1 mark]

c) Steam (2 marks)

Substitution: useful heat = $34,62,000 \times 0.72 = 24,92,640 \text{ kcal/h}$ [1 mark]; steam = $24,92,640/(665 - 105)$

Result: **Steam $\approx 4,451 \text{ kg/h}$** [1 mark]

d) Coal saving and payback (3 marks)

Formula: $\text{Coal} = \text{steam} \times (h - h_{fw}) / (\eta \times \text{GCV})$

Substitution: $24,92,640 / (0.78 \times 4,200) = 760.9 \text{ kg/h}$ [1 mark]; $\times 8,000 = 6,087 \text{ t/yr}$; $\times ₹ 6,500 = ₹ 3,95,66,000$ [1 mark]; $\text{payback} = 6.0/3.96$

Result: **Coal saved $\approx 6,087 \text{ t/yr} \approx ₹ 3.96 \text{ crore}$; payback $\approx 1.5 \text{ years}$** [1 mark]

e) Environmental benefit (1 mark)

Substitution: $\text{CO} = 6,000 \times 0.14 \times 1.25 = 1,050 \text{ kg/h}$ destroyed. The guidebook lists reduction in pollution as a direct benefit: burning toxic combustible wastes such as CO and carbon black off-gas both recovers heat and cuts emissions. [1 mark]

Marking note: $\pm 2\%$ tolerance; method marks for the air calculation by volume.

L-6 [4P2CEM064 | Chapter 9: Heat Exchangers | Optimum cleaning interval for a fouling heat recovery exchanger]

A regenerative exchanger recovers 800 kW right after cleaning. Its recovery falls steadily as it fouls; a test 60 days after cleaning showed 650 kW. The shortfall is made up by a natural gas heater (efficiency 85%, GCV 9,200 kcal/Nm³ ($\approx 38.5 \text{ MJ/Nm}^3$), ₹ 45 per Nm³) running 24 h/day. Each cleaning costs ₹ 60,000 including labour and bypass operation. The plant presently cleans every 90 days and operates 330 days a year.

- a) Calculate the rate of fall in recovery and the cost of 1 kWh of make-up heat. (2 Marks)
- b) Write the average daily cost (fouling plus cleaning) as a function of cleaning interval T and find the optimum interval. (4 Marks)
- c) Calculate the average daily cost at the optimum and at 90 days, and the annual saving. (3 Marks)
- d) State two measures, other than cleaning, to slow fouling. (1 Mark)

L-6 Ans (model answer with marking scheme)

Given: Recovery 800 kW at day 0; 650 kW at day 60; gas η 0.85, GCV 9,200 kcal/Nm³ ($\approx 38.5 \text{ MJ/Nm}^3$), ₹ 45/Nm³; cleaning C = ₹ 60,000; present T = 90 days; 330 days/yr.

a) Fouling rate and heat cost (2 marks)

Formula: $a = (800 - 650)/60$; cost per kWh = $860 / (\eta \times \text{GCV}) \times \text{price}$

Substitution: $a = 2.5 \text{ kW per day}$ [1 mark]; $860 / (0.85 \times 9,200) = 0.110 \text{ Nm}^3/\text{kWh} \times ₹ 45$

Result: **Recovery falls 2.5 kW/day; make-up heat costs $\approx ₹ 4.95 \text{ per kWh}$** [1 mark]

b) Optimum interval (4 marks)

Formula: Extra cost on day t = $a \times t \times 24 \times 4.95 = 297t \text{ ₹/day}$; over T days = $297T^2/2$; average = $C/T + 148.5T$; minimum where $d\text{Avg}/dT = 0 \rightarrow T^* = \sqrt{C/148.5}$

Substitution: $2.5 \times 24 \times 4.95 = ₹ 297 \text{ per day per day}$ [1 mark]; average = $60,000/T + 148.5T$ [1 mark]; $T^* = \sqrt{60,000/148.5} = \sqrt{404}$ [1 mark]

Result: **Optimum cleaning interval $\approx 20 \text{ days}$** [1 mark]

c) Costs and saving (3 marks)

Substitution: at $T^* = 20.1$: $60,000/20.1 + 148.5 \times 20.1 = 2,985 + 2,985 = ₹ 5,970/\text{day}$ [1 mark]; at 90 days: $667 + 13,365 = ₹ 14,032/\text{day}$ [1 mark]; $(14,032 - 5,970) \times 330$

Result: **Saving $\approx ₹ 26.6 \text{ lakh per year by cleaning about every 20 days}$** [1 mark]

d) Other measures (1 mark)

Keep fluid velocity high and avoid low-flow zones; filter or strain the dirty stream; control process temperature to avoid deposition; trend U or duty to trigger cleaning (the guidebook advises maintenance intervals set by cost–benefit criteria). [1 mark]

Marking note: $\pm 2\%$ tolerance; full marks for a correct graphical or tabular optimum.

..... End of Section III

Answer key – Section I

Q	Ans	Q	Ans	Q	Ans	Q	Ans	Q	Ans
1	d	11	a	21	c	31	b	41	a
2	b	12	a	22	c	32	c	42	b
3	a	13	c	23	b	33	a	43	d
4	a	14	b	24	d	34	d	44	a
5	b	15	d	25	b	35	b	45	a
6	a	16	d	26	c	36	c	46	d
7	d	17	a	27	b	37	b	47	b
8	d	18	a	28	c	38	d	48	c
9	c	19	c	29	a	39	b	49	c
10	d	20	d	30	c	40	b	50	a